European
Commission

JRC SCIENCE FOR POLICY REPORT

The use of woody biomass for energy production in the EU

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2021

Joint
Research
Centre

EUR 30548 EN

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EU Science Hub
https://ec.europa.eu/jrc

JRC122719

EUR 30548 EN

PDF ISBN 978-92-76-27867-2 ISSN 1831-9424 doi:10.2760/831621
Print ISBN 978-92-76-27866-5 ISSN 1018-5593 doi:10.2760/428400

Luxembourg: Publications Office of the European Union, 2021

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How to cite this report: Camia A., Giuntoli, J., Jonsson, R., Robert, N., Cazzaniga, N.E., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo, J.I., Mubareka, S., The use of woody biomass for energy purposes in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-27867-2, doi:10.2760/831621, JRC122719

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Acknowledgements

This study was conducted as part of the JRC's long term mandate to assess the EU and global biomass supply and demand and related sustainability. This is a long-term institutional commitment of the JRC that initiated in 2015. The authors would like to acknowledge the support of the technical experts of the relevant Inter-Service group on Biomass Supply and Demand Assessment in the European Commission, chaired by T. Schleker from the Directorate General for Research and Innovation. Comments from this Inter-Service group were essential during the execution of this work to put it in the proper policy context.

We thank ENFIN (the European National Forest Inventory Network) for their precious collaboration to harmonise the data on forest biomass and forest available for wood supply. We also would like to thank the experts in the Member States who validated the data on salvage loggings.

The authors also thank Javier Sanchez Lopez from the Knowledge Centre for Bioeconomy Coordination Team for his reviews and edits, Alessandro Cescatti for his insights on the union between satellite imagery and field data, Roberto Pilli and Anu Korosuo for their useful comments.

Executive summary

In May 2020, the EU Biodiversity Strategy for 2030 (COM/2020/380) was adopted. In the communication, under section 2.2.5 ("Win-win solutions for energy generation"), the Commission committed to publishing this report on the use of forest biomass for energy production in order to inform the EU climate and energy policies that govern the sustainable use of forest biomass for energy production and the accounting of associated carbon impacts, namely the Renewable Energy Directive, the Emissions Trading Scheme (ETS), and the Regulation on land use, land use change and forestry (LULUCF).

The forest-based sector has been identified as part of the solution to many global challenges and a key contributor to EU objectives. Many EU policies influence forest management, the forest-based sector and forest ecosystems. The principal questions surrounding the use of woody biomass for energy production in the EU and impacts on forests are indeed very broad. It was therefore necessary to set boundaries to the study at the onset: the study would take stock of the available data related to the use of woody biomass for bioenergy; assess the uses of woody biomass in the EU with a focus on bioenergy; provide suggestions on how to improve the knowledge base on forests in a harmonised way; and expand the evidence basis by highlighting pathways that minimise trade-offs between climate mitigation and biodiversity conservation. The study does not rely on quantitative foresight exercise to establish the scale of future bioenergy demand, and consequently the interventions assessed are potential ones, but we do not claim they are the most likely to take place. This study presents the policy implications deriving from the evidence basis. To address the mandate of this study, and in an attempt to provide concrete support to policymakers, we summarise the main implications of the findings from this study in the framework of the policy areas that address the governance of wood-based bioenergy at the EU level.

European climate and energy policies are improving. The EU will now measure the climate impact of forest management using the "Forest Reference Level" (FRL) concept (Regulation 2018/841) within the Land Use, Land-Use Change and Forestry (LULUCF) sector. The FRL is the projected level of forest emissions and removals, estimated by each EU Member State for the period 2021-2025, against which future emissions and removals will be compared. Whereas in the past these projections could include policy assumptions, with the risk of inflating the real impact of mitigation actions, the FRLs described in Regulation 2018/841 are exclusively based on the continuation of forest management practice and wood use, as documented in a historical reference period (2000-2009). In this way, the age-related forest dynamics are taken into account, and policy assumptions are excluded. The FRLs thus ensure that the carbon impact of any change in management or wood use relative to a historical period is fully counted towards the country climate targets.

With respect to energy policy, under the Directive on renewable energy (Directive 2009/28/EC) for the 2010-2020 period, sustainability criteria applied only to the use of biofuels and bioliquids. The recast of the Renewable Energy Directive (Directive 2018/2001, known as REDII), to be transposed by Member States by June 2021, strengthens the EU sustainability criteria for bioenergy by extending their scope to solid biomass and biogas used in large-scale heating/cooling and electricity installations. In addition, REDII introduces new risk-based sustainability criteria for forest biomass, with the aim to ensure compliance with sustainable forest management laws and principles (e.g. legality, regeneration, protection of sensitive areas, minimization of biodiversity impacts; and maintenance of the long-term forest productivity) and that the carbon impacts of bioenergy are properly accounted for under the LULUCF sector. Following a risk-based approach, compliance can either be demonstrated through effective national or regional legislation, or through management systems at the sourcing area level. REDII includes minimum GHG emission saving thresholds for biofuels, and biomass in heat and power and minimum efficiency criteria for bioelectricity-only installations.

The EU legislation focuses the definition of environmentally sustainable bioenergy on biodiversity conservation and climate change mitigation because bioenergy sits at the nexus of two of the main environmental crises of the 21st century: the biodiversity and climate emergencies. Wood-based bioenergy has the potential to provide part of the solution to both crises, but only when biomass is produced *sustainably* (and is used efficiently). This is especially critical considering that forest ecosystems are generally not in good condition in Europe.

But what does "sustainable" mean? Currently, all EU Member States support the principle of multifunctionality of forests and the concept of sustainable forest management, which indicates, in this context, to seek the most suitable management systems to maintain and balance the provision of multiple functions over time. The operationalisation of this concept is necessarily adapted to local socio-economic, political and biophysical contexts, and local priorities will also be affected by societal values. For example, forest management goals might be focused more on protection and nature conservation or they might favour wood production. Implementing sustainable forest management should aim at balancing multiple functions and securing their continued provision in the future.

We highlight the fact that the governance of bioenergy sustainability is characterised by uncertainty about consequences, diverse and multiple engaged interests, conflicting knowledge claims and high stakes, and can thus safely be dubbed 'a wicked problem'. In other words, as scientists, we need to clearly understand our role in this debate: we can gather and synthesise evidence highlighting problems and possible solutions as honest brokers[1] of policy options, but we cannot identify the 'right' policy tool or the 'right' policy principle to follow because those issues are within the realm of the political arena and no amount of scientific research will appease ethical disputes.

The study begins with a quantitative assessment of the supply and use of woody biomass. Available data sources about woody biomass for bioenergy in the EU are assessed for how they can be used for a harmonised EU-level analysis. We examine numerous data sources that provide information on different pieces of the wood-based bioenergy system puzzle because, unfortunately, no single data source encompasses the whole system. As a result, we generate the coherent dataset needed for this study through an in-depth scrutiny, collation and interpretation of several sources whose scope, coverage, units and so on, differ between one another.

In our quantitative analysis we consider wood-based bioenergy as part of the wider forest bioeconomy, thus in the context of sustainable forest management and the growing demand of wood for products manufacturing and bioenergy production, although it should be noted that market forces and economic or socioeconomic drivers are not part of the analysis. We reconstruct the woody biomass flows, highlighting the interlinkages and the generally circular nature of wood use within the EU forest-based sector, and the corresponding relative size and role of wood-based bioenergy. Our processing of the data on reported wood removals and the net annual increment in EU forests show an increase in the intensity of harvesting from 2009 to 2015. According to our estimates, the EU-level fellings to increment ratio in 2015 was in the range of 75%-85%. We also address natural disturbances and the consequential salvage loggings that have dramatically increased since 2014, mainly in Central Europe, bringing significant amounts of damaged wood to the market. Furthermore, we derive estimates of total aboveground biomass and reconstruct the detailed composition of the woody biomass input mix used for bioenergy in the EU.

Results of this analysis show an increasing overall use of woody biomass in the EU in the past two decades (around 20% since 2000), except for a marked low noted after the financial crisis of 2008. Similarly, the subset of woody biomass used for the specific purpose of energy has

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[1] A term adopted from Pielke, R. (2007) The Honest Broker: Making Sense of Science in Policy and Politics. Cambridge University Press. https://doi.org/10.1017/CBO9780511818110

followed an increasing trend until 2013 (about 87% from 2000-2013), after which the growth has slowed. According to our analysis, wood-based bioenergy production is, to a large extent, based on secondary woody biomass (forest-based industry by-products and recovered post-consumer wood), which makes up almost half of the reported wood use (49%). Primary woody biomass (stemwood, treetops, branches, etc. harvested from forests) makes up at least 37% of the EU input mix of wood for energy production. The remaining 14% is uncategorised in the reported statistics, meaning it is not classified as either a primary or secondary source. Based on our analysis of the woody biomass flows, the source is more likely to be primary wood. Wood-pellets imports have a minor role in the EU after Brexit.

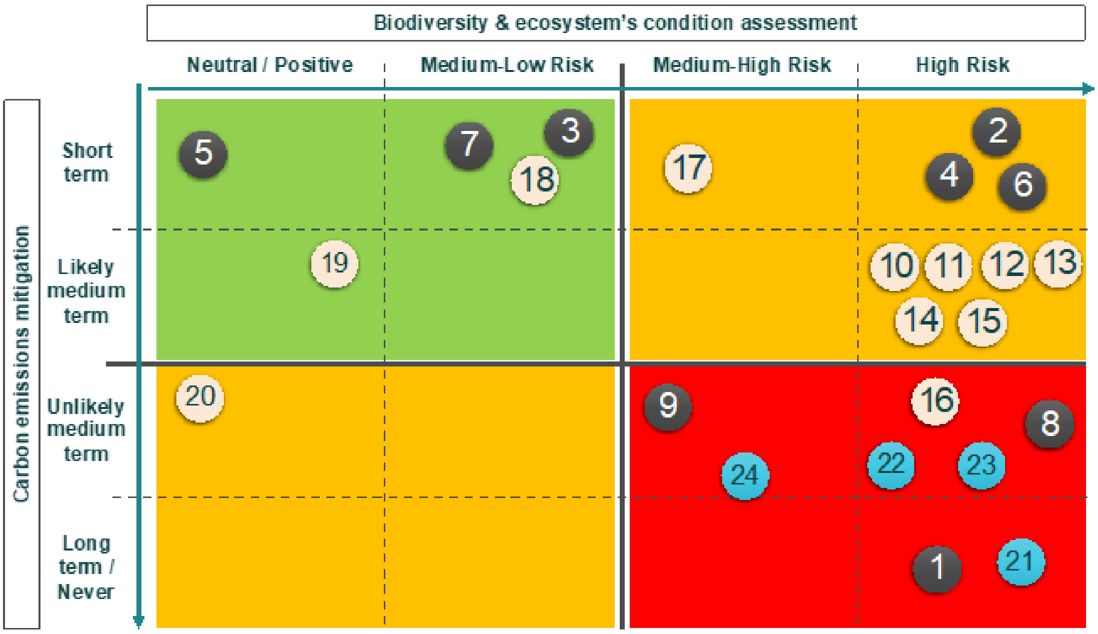
Further characterising the primary woody biomass used, we estimate that roughly 20% of the total wood used for energy production is made up of stemwood, while 17% is made up of other wood components (treetops, branches, etc.). Based on available knowledge, at least half of the stemwood used for energy is assumed to be derived from coppice forests, which are particularly important in Mediterranean countries. Coppice forests, for the most part, provide many ecosystem services, and this management system has relevant socio-economic functions in many rural areas. However, in large areas coppices are no longer managed, resulting in old or overgrown declining stands; it is suggested to encourage active coppice restoration or conversion into high forest, depending on local conditions, to enhance the capacity of these ecosystems to store carbon and supply wood and other services.

Our quantitative analysis reveals considerable inconsistencies in reported data: for all the years analysed (2009 to 2015), it is estimated that in the EU, the amount of woody biomass *used* in the manufacturing of wood-based products and for energy production exceeds the total amount of reported as *sources* by more than 20%, with large differences among Member States. Our analysis, based on a breakdown of the flows of woody biomass, suggests that the gap between reported uses and sources of woody biomass can be attributed to the energy sector. In addition, reliable knowledge on the origin of wood used for energy production is crucial for the analysis necessary to safeguard a sustainable and resilient resource use. Unfortunately, we observe that the tendency of reporting as unknown origin the wood used for energy production is increasing. We conclude that it is of utmost importance to improve the availability and quality of data with respect to the forest-based sector, and the energy use of wood in particular.

Earth Observation is becoming increasingly useful in facilitating harmonised and timely assessments. Satellite and airborne data are more and more used by the European National Forest Inventories to supplement ground-based surveys. Using Earth Observation products, we have developed a forest biomass map of Europe that is in line with harmonised statistics of forest area and biomass stock provided by the National Forest Inventories. Robust biomass maps such as these show the potential for multiple applications of Earth Observation data that integrate various geospatial forest and environmental properties. A vast amount of high-resolution satellite imagery is freely available through the EU Copernicus programme, while biomass mapping from space is rapidly evolving thanks to new satellites with enhanced sensitivity to forest biomass. Substantial improvement in the knowledge of the spatial distribution and dynamics of forest biomass from space can be expected in the near future.

The quantitative analysis carried out in this study confirms the basic premise that this complex system includes multiple economic sectors and social actors, and presents many causal linkages and feedback loops. It also shows that the responses of the forest-based sector are influenced by policy objectives, regulations and by the impacts of climate change and human intervention on future growth rates of forests and on the frequency and magnitude of natural disturbances. We therefore turn to the main, if not a more generalised, question of the study, which is: how can we ensure that pathways for the provision of woody biomass, following increased demand for wood, are not detrimental to climate and to biodiversity? In this study, we assess three categories of interventions and their potential impacts: removal of logging residues, afforestation and conversion of natural forests to plantations. These three interventions were chosen because they are considered as practices that aim to supply 'additional' biomass, i.e. growing biomass that would not be produced in the absence of bioenergy demand, or using biomass, such as residues and wastes, which would otherwise decompose or be burned on site. We acknowledge that, until now, many of these responses have not been triggered as a direct consequence of bioenergy expansion, but they are high on the agenda of potential climate mitigation strategies and could occur, in the EU or outside, as a direct or indirect effect of increased EU demand for forest biomass for wood products and bioenergy. Our findings do not claim to capture the whole range of possible risks and benefits associated with forest management interventions linked to bioenergy.

The impacts of the three interventions on biodiversity and various other attributes that define the condition of ecosystems are evaluated through an extensive literature review and are then synthesised in a qualitative assessment through the definition of pathway archetypes (summarised in the figure below). The impacts of these archetypes are characterised in one of four risk categories: high risk, neutral-positive, medium-high risk and medium-low risk. The impacts of these pathway archetypes on carbon emissions are also extracted from existing lifecycle analysis (LCA) literature and classified into one of four categories depending on the potential carbon payback time: short-term, likely medium-term, unlikely medium-term and long-term/never. We then compare the impacts of the different management practices on both biodiversity and climate change and propose "win-win" management practices that contribute positively to both. We also identify "lose-lose" situations whereby the pathway would damage forest ecosystems without providing carbon emission reductions in policy-relevant timeframes. Win-win management practices that benefit climate change mitigation and have either a neutral or positive effect on biodiversity include removal of slash (fine, woody debris) below thresholds defined according to local conditions, and afforestation of former arable land with mixed forest or naturally regenerating forests. Lose-lose pathways include removal of coarse woody debris, removal of low stumps, and conversion of primary or natural forests into plantations. We also define pathways with trade-offs that may, for example, help mitigate carbon emissions but be detrimental to local biodiversity or vice versa. We present the policy implications of this study as an input to the further development of the governance of sustainable forest bioenergy.



	ID	Pathway description
Logging residues removals	1	Coarse WoodyDebris removal
	2	Fine Woody Debris (Slash + foliage/needles) removal above landscape threshold
	3	Fine Woody Debris (Slash + foliage/needles) removal below landscape threshold
	4	Fine Woody Debris (Slash - Coniferous) removal above landscape threshold
	5	Fine Woody Debris (Slash - Coniferous) removal below landscape threshold
	6	Fine Woody Debris (Slash - Deciduous) removal above landscape threshold
	7	Fine Woody Debris (Slash - Deciduous) removal below landscape threshold
	8	Low stumps removal above landscape threshold
	9	Low stumps removal below landscape threshold
Afforestation	10	Natural grassland afforestation with monoculture plantation
	11	Natural grassland afforestation with polyculture plantation
	12	Natural grassland afforestation with other planted forest
	13	Anthropogenic heathland afforestation with monoculture plantation
	14	Anthropogenic heathland afforestation with polyculture plantation
	15	Anthropogenic heathland afforestation with other planted forest
	16	Natural forest expansion on anthropogenic heathland
	17	Former agricultural land afforestation with monoculture plantation
	18	Former agricultural land afforestation with polyculture plantation
	19	Former agricultural land afforestation with other planted land managed with low intensity
	20	Natural forest expansion on former agricultural land
Conversion to plantation	21	Conversion of primary, old-growth forest, to plantation
	22	Conversion of native naturally regenerating forest to monoculture plantation
	23	Conversion of native naturally regenerating forest to polyculture plantation
	24	Conversion of native naturally regenerating forest to other planted forest managed with low intensity

Concerning the policy implications of our findings, we first consider the climate and energy legislation in place and the linkages between these, because there are still misunderstandings in the scientific literature and in the public debate. The recast Renewable Energy Directive (REDII directive 2018/2001) assumes zero emissions at the point of biomass combustion[2]. Bioenergy is not accounted for in the energy sector because these emissions are *already* counted in the LULUCF sector (Regulation 2018/841) as a change in carbon stocks. Therefore, it is incorrect to say that bioenergy is assumed "carbon neutral" within the broader EU climate and energy framework. The carbon impact of any change in management or wood use relative to a historical period is fully counted in the LULUCF sector, against the FRLs. The consequence of this approach is that trade-offs exist: any additional wood harvested for bioenergy purposes (or a greater energy use of wood) may reduce fossil fuel emissions under the ETS or effort sharing sectors but will also generate an accounting debit in LULUCF if it brings emissions beyond the FRL, for example if this extra harvest goes beyond the harvest expected in the FRL and is not compensated by an equivalent extra forest growth. Since any LULUCF accounting debit would require additional emission reductions in other sectors to meet the country climate target, the

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[2] Similar considerations apply to the counting of bioenergy emissions in the EU Emission Trading Scheme (ETS), which is not explicitly analysed further here

overall climate benefit of any extra wood used for bioenergy should be carefully evaluated. We identify factors that may potentially lead to unintended outcomes, for example, increased carbon emissions due to an excessive use of forest bioenergy. These factors include a mismatch of policy incentives for different target groups (REDII stimulates bioenergy demand by economic operators, while LULUCF disincentivises countries to harvest beyond certain limits) and poor communication among actors. Managing the risk of unintended outcomes requires, first and foremost, a greater awareness by countries of the REDII/ETS-LULUCF links and the associated trade-offs. This awareness should then be reflected in the national relevant plans (National Energy & Climate Plans), through coherent policies and financial incentives at national and local level, combined with a timely and reliable monitoring of the use of wood for energy production. As a general principle, prioritising residues and the circular use of wood remains key for maximising the positive climate impact of wood-based bioenergy. Qualitative criteria have been proposed in the literature to identify bioenergy pathways with low risks of increased carbon emissions compared to fossil fuels in agreement with many of the win-win pathways identified in this report. These criteria may help the implementation of energy and climate legislation by countries and bioenergy operators.

We note that, although the LULUCF regulation 2018/841 is an important step towards a complete forest GHG accounting framework, in the context of Europe's new 2030 climate target (COM/2020/562) we see an opportunity to start treating the LULUCF sector like any other sector, i.e. with no or limited filtering of the reported LULUCF GHG fluxes through a complex set of accounting rules. This would help to simplify the LULUCF jargon, facilitate communication and it would be more evident that the whole carbon impact of bioenergy is accounted for. This may ensure greater transparency, also in the accounting of forest bioenergy emissions.

Further to these thoughts, we are of the opinion that several negative impacts associated with the pathways reviewed in this study could be effectively minimised through swift and robust implementation of the REDII sustainability criteria related to forest biomass, which will be further operationalised through the upcoming EU operational guidance on the evidence for demonstrating compliance with the forest biomass criteria. Nonetheless, compliance with the REDII criteria for sustainable forest management relies, in the first instance, on the existence of national forest legislation or on management systems at the level of the sourcing area. Therefore, while the focus of this report is on the EU legislative framework, the effective implementation will depend on the fitness of national legislation and guidelines, as well as their effective implementation. We recommend that countries also test their national forestry legislations against the findings of this report, to make sure that win-win pathways are promoted while lose-lose practices are avoided. At the same time, both EU and national legislations should strive to create the right incentives to promote the win-win pathways and good practices highlighted in this report.

Nonetheless, compliance with the REDII criteria for sustainable forest management relies, in the first instance, on the existence of national forest legislation or on management systems at the level of the sourcing area. Therefore, while the focus of this report is on the EU legislative framework, the effective implementation will depend on the fitness of national legislation and guidelines,. We recommend that countries also test their national forestry legislations against the findings of this report, to make sure that win-win pathways are promoted while lose- lose-lose practices are avoided.

Concerning opportunities for the operationalisation of the REDII criteria, we recognise that most voluntary schemes have provisions for coarse-woody debris (CWD) retention levels. However, given the incentive created by the bioenergy demand to increase the collection and removal of these materials, it is essential that countries define and enforce appropriate and precautionary landscape retention thresholds across sourcing areas that produce bioenergy feedstock for all categories of residues, and that they discourage the collection of low-stumps and CWD. Furthermore, some certification standards, such as those of the FSC (Forest Stewardship Council), already forbid the clearing of natural forests into plantations. We therefore suggest that biomass produced from plantations established on recently cleared natural forest cannot be eligible for bioenergy use. This would also remove pressure for future conversions by lowering the demand of wood from these plantations, at least for energy use.

The LULUCF criteria set out in REDII Art. 29(7) require accounting of forest biomass stock and sinks as part of the economy-wide National Determined Contributions (NDCs) under the Paris Agreement. For countries that do not have an NDC or do not include LULUCF within their NDCs, it is crucial that evidence is provided that carbon stocks and sinks are maintained or enhanced for any imported biomass, at both the national or the relevant subnational level.

While REDII is a step forward in ensuring the sustainability of bioenergy consumed in the EU, improvements could still be made to minimize damaging pathways. More specifically, REDII indicates specific no-go areas for agricultural biomass, meaning that biomass for bioenergy cannot be directly produced from land that was, at any time after 2008, classified as highly biodiverse grasslands, primary forest, highly biodiverse forest, or protected areas. However, these criteria do not apply to forest biomass (except for the protected areas criterion). Expanding such land criteria to forest biomass would introduce additional safeguards to ensure that forest biomass for energy is not associated with the afforestation pathways that have the most negative impacts, i.e. those on high-nature value grasslands or anthropogenic heathlands, and it would also forbid the sourcing of wood from plantations established on converted old-growth, primary forest for energy feedstock.

The current significant gap in data represents a major obstacle to the effective governance of wood-based bioenergy policies at national scale. Efforts to review reporting procedures may also result in a better correspondence between the three data sources most extensively used in this study (JFSQ, JWEE and NREAP progress reports), thus reducing the notable inconsistencies in the data. Without reliably knowing how much and what type of forest biomass is used for bioenergy, no effective policy can be implemented.

As highlighted by the EU Bioeconomy Strategy (COM/2018/673), holistic governance is required to move towards a sustainable and circular bioeconomy. Any additional demand for wood for bioenergy will simply add to the overall demand for wood for other uses, meaning that even if wood for energy is subject to strict sustainability criteria, wood for other purposes might still be produced through detrimental practices and pathways. Therefore, further developing, operationalising and expanding the requirements of sustainable forest management to all forest products consumed in Europe, irrespective of final use and geographical origin, would be an effective measure to promote a sustainable forest-based sector as a whole.

Throughout the chapters of this report, we present various recommendations for future research. These include, for example, expanding this analysis to other types of forest management interventions, understanding the degree to which interventions might be driven by the bioenergy sector and interactions with other branches of the forest-based sector; quantifying the market distortions due to natural disturbances, as well as understanding why these are increasing in frequency, further developing the applications of Earth observation data. This should be done in coordination with the Knowledge Centre for Biodiversity and the Biodiversity Information System for Europe so that data collection and research about biodiversity is prioritised to fill critical gaps. Furthermore, additional modelling exercises that aim to capture the impacts of changes in forest management practices and quantify the availability of secondary woody biomass given fluctuations in markets for primary sources in all sectors would be highly desirable.

To conclude, this report and the future research lines indicated focus on expanding the evidence basis at the disposal of decision-makers. Differences in ethical values regarding the interaction between humans and nature clearly play a role in defining what ‘sustainable’ means. We believe that these divergences in values should be acknowledged and discussed explicitly, also within the scientific community, in order to de-toxify the debate surrounding the sustainability of wood-based bioenergy.

Policy context

The 2030 Biodiversity Strategy (BDS), under section 2.2.5 (Win-win solutions for energy generation) announces that the Commission will publish results from its Biomass Study (see section on “Related and future JRC work”) on the use of forest biomass for energy production. According to the Strategy, this report will inform important policy dossiers in 2021, including the review and revision, where necessary, of the level of ambition of the Renewable Energy Directive, the Emissions Trading Scheme, and the Regulation on land use, land use change and forestry (LULUCF) set for 2021. This output is listed as a specific action in the Biodiversity Strategy Action Plan (Study on the sustainability of the use of forest biomass for energy production), whilst the broader Biomass Study is listed as a separate (ongoing) action.

Related JRC work

Biomass assessment

The "Assessment of the EU and global biomass supply and demand and related sustainability" (the JRC Biomass Study) is a long-term institutional commitment of the JRC that initiated in 2015. It operates under a mandate agreed by eleven policy DGs at directors' level and coordinated within a dedicated inter-service group (“ISG Biomass”) which is led by RTD.D1.

The Biomass study covers biomass assessments from all primary production sectors (forestry, agriculture, fisheries, algae) and has become a critical part of an Action of the Bioeconomy Strategy Action plan: Action 3.3.1, "Enhance the knowledge on the bioeconomy, including on biodiversity and ecosystems to deploy it within safe ecological limits, and make it accessible through the Knowledge Centre for Bioeconomy" since the publication of the 2018 updated EU Bioeconomy Strategy.

The outcomes from this activity are consolidated in an internal annual progress report and a publicly available “Science for Policy” report on a biennial basis. The last Science for Policy report was produced in 2018.

EU Observatory on deforestation and forest degradation

In the Communication to step up EU action to protect and restore the World’s forests (COM(2019) 352), the Communication prioritizes actions on 1) consumption footprints and supply chains, 2) bilateral and multilateral collaboration with producing countries, 3) international cooperation, 4) financial investment in sustainable land-use, 5) research and innovation to produce accessible high-quality information on forests and commodity supply chains. This Communication highlights the importance of the World's forests, warning of the threats to forests as well as the consequences of losing them.

The objective of the EU Observatory on deforestation, forest degradation, changes in the world’s forest cover, and associated drivers, as described in the Communication, is “to facilitate access to information on supply chains for public entities, consumers, and businesses”.

Knowledge Centre for Bioeconomy

The Knowledge Centre for Bioeconomy (KCB) is the Commission's central knowledge hub on the bioeconomy. The overall provision and analysis of knowledge, scientific evidence and collective intelligence (including through a Community of Practice) for bioeconomy-related policy making, from within and outside the Commission is coordinated within the KCB.

Quick guide

Introduction, scope and structure of report.

Chapter 2. This chapter details the sources of information that are relevant to understand how the wood energy value chain is governed by various factors such as the industrial use of wood and forest management, and makes sense of the information that can be retrieved from these different sources.

Chapter 3. This chapter contains a quantitative analysis of the wood-based bioenergy sector, including the relative size of the overall forest-based sector, biomass balance sheets and flows, and net trade of woody biomass sources. Temporal trends are also reported. Primary and secondary wood supply are discussed, looking into the composition of feedstocks. Due to the interlinkages of the forest-based sector, both material as well as energy uses of woody biomass are considered in the assessment. An analysis of inconsistencies in reported data is made. Unique data on salvage loggings in EU are presented indicating implications of natural disturbances on wood supply.

Chapter 4. This chapter provides an overview of the existing standing biomass stock in European forests and describes the efforts made by the JRC in collaboration with national experts towards a harmonised assessment of the forest above-ground biomass availability in the EU and ultimately a seamless 1-ha resolution map. A reference database of forest biomass stock and stock available for wood supply at both national and sub-national level for all European countries, using the best available biomass data, is described.

Chapter 5. This chapter focusses on a review of the current knowledge on sustainability assessments in the EU that bridge the literature and experts in ecology with the literature and expertise in the bioenergy field, with a focus on climate change and biodiversity, as well as the interlinkages between these two. Win-win (and lose-lose) options in terms of climate change mitigation as well as preserving or improving on ecosystem's health and biodiversity are identified, followed by a discussion of options to improve the biodiversity-friendliness of biomass value chains from forest.

Policy implications & future work

1 Introduction & scope

The demand for biomass is increasing worldwide yet climate change, increasing pressures on the environment and large-scale loss of animal and plant species are threatening biomass availability. The challenge we face is thus to reconcile this increased demand for biomass, aware of all its advantages in replacing fossil-based materials and fuels, with the sustainable management, including protection and restoration of the forest ecosystems that are producing it.

The success with which we will be able to meet the ambitions of the European Green Deal, to take the path of a green recovery towards making Europe the first climate neutral continent and to restore biodiversity, will depend to a large extent on the ways in which we use our natural resources from the land and the sea to produce food, materials and energy. The purpose of this study is to further our understanding on whether or not woody biomass for energy can be produced, processed and used in a sustainable and efficient way to optimise greenhouse gas savings and maintain ecosystem services, all without causing deforestation, degradation of habitats or loss of biodiversity.

The forest-based sector has been identified as part of the solution to many global challenges and key contributors to EU objectives. Many EU policies influence forest management, the forest-based sector and forest ecosystems: Climate change (Land Use, Land Use Change and Forestry), Biodiversity, Circular economy, Bioeconomy, Rural development, Renewable Energy, Industry (to name a few). Not all of these are always complimentary and synergistic across policies, or throughout all levels of actors: from the practitioners working in the forest and forest-based sector to the EU-level policy makers. It is fundamental that the right equilibrium is struck.

The boundaries for this study are necessarily limited with respect to the full scope of the questions at hand. This report takes stock of the available data related to the use of woody biomass for bioenergy, assesses the uses of woody biomass in the EU with a focus on bioenergy, provides suggestions on how to improve the knowledge base of forests in a harmonised way, expands the evidence basis by highlighting forest management practices that minimise trade-offs between climate mitigation and biodiversity conservation, presents the policy implications derived from this evidence, and finally makes some non-exhaustive recommendations for future research. The focus of this report is on the use of woody biomass for energy production. The bioenergy issue is presented within the broader framework of sustainable forest management and the forest-based sector. Some sections of this report address these, providing comprehensive figures to put forest bioenergy into perspective and understand the various interactions. We detail and quantify as much as possible the share of assortments, from both primary and secondary sources, that enter the energy mix.

Although this report does not aim to provide a holistic view of the situation in EU forests today, figures on forest biomass harvesting are described, with the maximum level of detail that available statistics allow, and even beyond those with the help of modelling techniques (e.g. using allometric equations, biomass expansion factors and biomass harmonisation approaches developed with National Forest Inventories). A brief general description of the forest-based sector markets is provided based on critical analysis of publicly available statistics. In this respect we maintain a focus on the general trends, and touch upon the short-run effects of salvage logging. The report is intended to be factual, minimising quantitative assumptions and avoiding speculations to the possible extent.

This report has limitations on the issues of sustainability. It does not aim to provide absolute answers on which pathways are sustainable or not, but rather expands the evidence basis for policy decisions through a literature review and qualitative knowledge synthesis. Of all the facets of forest bioenergy sustainability, we focus on the two issues of climate change and ecosystems' health. Thus, we exclude many other aspects that characterize the broader bioenergy sustainability such as the role of bioenergy on electricity grid stabilization; energy security; rural development, income, and employment; other environmental impacts like air pollution; other non-GHG climate forcers; etc.

This work does not reassess the carbon/climate impact of forest bioenergy. This was analysed in depth in the Impact Assessment of REDII (see Annex 9 of the IA[3]) and it is out of scope here.

The report addresses management practices predominantly associated to bioenergy uses, recognising that these are almost never exclusive uses. Specifically, we have proposed to address three interventions which could potentially be driven, partially or completely, by bioenergy demand: increased logging residues harvest, afforestation/reforestation, and conversion of natural forests to plantations (the third of which is a subset of the second). We examine the impacts of these interventions on ecosystems, independently on whether they are driven by bioenergy or not. If they have been found to be driven by bioenergy, then the impacts can be attributed to bioenergy, but this is not assessed in this report.

Quantifying the woody biomass that is circulating in the energy sector requires a deep analysis into the statistics available on the topic. Chapter 2 of this report is dedicated to describing the various data sources that are available, their scope and applications. Special attention is given to the datasets that are further used for the analysis presented in the second chapter.

Chapter 3 is dedicated to the analysis of the forest-based sector, with a focus on bioenergy. In this chapter we give an overview of the breakdown of woody biomass used for bioenergy in the EU and analyse the trends. An in-depth analysis is made of the sources of woody biomass, including all wood fibres from all sources, including from salvage logging. The circularity that characterises the forest-sector is also described through an analysis of woody biomass flows in the EU. This chapter is based on statistical analysis and expert knowledge.

Chapter 4 describes how Earth Observation and statistics can be combined to quantify the natural capital in our forests. It illustrates the techniques used to both harmonise data across the EU in collaboration with National Forest Inventory experts and remote sensing data. The mapping of forest above-ground biomass and areas of forest available for wood supply into seamless, high resolution, spatially explicit maps are a valuable product, especially when a time-series can be reconstructed.

Chapter 5 focusses on the carbon and biodiversity impacts of forest bioenergy. A literature-based approach is applied to assess the impact on carbon and biodiversity of the different bioenergy pathways studied. The concept of sustainable forest management is approached in this last chapter, paving the way for a discussion on three specific interventions that are commonly, but not exclusively, associated to the demand for bioenergy. These are, through the lens of forest management, compared through a matrix to highlight the win-win and lose-lose settings.

Finally, we conclude with a description of the needs and prioritisation for future work on this topic.

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[3] https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

2 Sources of data on woody biomass from within and outside of forests for energy

The analysis of woody biomass uses for energy, its flows and its impacts, requires an in-depth assessment of the relevant value chains that link the primary production to the final use. Although no full dataset from public statistics describes woody biomass flows for energy specifically, several surveys and statistics provide information on different parts of the value chain. An important part of the work is to describe the woody biomass flows consists in analysing these different statistics to understand how they can be put together even though they differ in methodology, definitions and objectives. After defining the main reference definitions, this chapter lists the most relevant statistics, providing information on the EU forest-based sector that can be used to estimate wood supply, transformation and use for energy and material with a focus on the data sources used to develop the wood resources balances analysed in Chapter 3.

2.1 Definitions

This study of the use of woody biomass for energy and its relations to multipurpose forest management relies on several data sources and the screening of numerous publications in which the same terms may be used with different meanings. Therefore, to avoid misunderstandings, the most important and complex terms are defined below, complemented in the glossary at the end of this report.

2.1.1 Definitions related to forests and related indicators

Woody biomass can originate from different land-uses: forests, other wooded land and other land with tree cover. In Chapter 3, woody biomass flows are estimated from all types of land with trees, except when specified. Throughout the report, the FAO definitions of wooded lands are used. These definitions are as follows (for more details, see FAO, 2018).

Forests are defined as land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. This does not include land that is predominantly under agricultural or urban land use.

Since only a part of the forest can be harvested, a subset of forest is defined as Forest available for wood supply (Forest Europe, 2015): Forests where any environmental, social or economic restrictions do not have a significant impact on the current or potential supply of wood. These restrictions can be established by legal rules, managerial/owner’s decisions or because of other reasons.

Other wooded land (OWL) is defined as land not classified as “Forest”, spanning more than 0.5 hectares; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10 percent. This does not include land that is predominantly under agricultural or urban land use.

Other land with tree cover is defined as all land that is not classified as “Forest” or “Other wooded land” but is covered by some trees. These include tree orchards, agroforestry, trees in urban settings and palm trees.

Some possible solutions to produce more woody biomass for energy relate to reforestation and afforestation (see Chapter 5). In line with the FAO definitions, reforestation corresponds to the re-establishment of forest through planting and/or deliberate seeding on land classified as forest. This does not imply any change of land use. On the contrary, afforestation which is the establishment of forest through planting and/or deliberate seeding on land that, until then, was under a different land use, implies a transformation of land use from non-forest to forest.

The stock of wood in forests and other wooded land consists of living biomass and deadwood. In living biomass, above-ground biomass is defined as all biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage whereas below-ground biomass corresponds to all biomass of live roots except fine roots of less than 2 mm diameter. Deadwood denominates all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Deadwood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country. All these three types of woody biomass can be used for energy.

Most statistics about the stock report the growing stock, which is the volume over bark of all living trees with a minimum diameter of 10 cm at breast height (or above buttress if these are higher). It includes the stem from ground level up to a top diameter of 0 cm, excluding branches. This definition is less inclusive than the aboveground biomass but corresponds to the main part of the trees that is harvested and marketed. Moreover, it is estimated by most forest inventories with higher accuracy than is biomass, although National Forest Inventories may apply slightly different values of minimum diameter at breast height and top diameter thresholds, this makes the comparison of values more difficult.

Apart from biomass and growing stock, additional indicators are needed to understand how much biomass is available in the long run without depleting the resources. The net annual increment (NAI; Forest Europe, 2015) is the average annual volume of gross increment over the given reference period, minus that of natural losses on all trees, measured to the same minimum diameters as used to define the growing stock. NAIis commonly used as a benchmark against fellings (see below and Chapter 3). The gross annual increment (GAI; Forest Europe, 2015) is the average annual volume of increment over the reference period of all trees measured to the same minimum diameters as defined for the growing stock. It includes the increment on trees that have been felled or die during the reference period.

Fellings are defined as the average standing volume of all trees, living or dead, measured over bark to minimum diameters as defined for growing stock that are felled during the given reference period. This includes the volume of trees or parts of trees that are not removed from the forest, other wooded land or other felling sites (Forest Europe, 2015). The definition includes silvicultural and pre-commercial thinnings and cleanings left in the forest, as well as natural losses that are recovered (harvested). Because harvested natural losses are accounted for, this should be taken into account in the comparison of fellings with NAI to assess the sustainability of forest management. Removal of natural losses are also reported to Forest Europe (indicator 3.1) to enable the comparison.

Note that GAI, NAI and fellings are all estimated in growing stock over bark, therefore enabling direct comparisons. This differs from the wood product definitions below, and in particular from the harvested roundwood which is usually reported under bark (i.e., excluding bark) and includes products from branches and stumps. Conversion coefficients are required to allow comparison of these numbers.

2.1.2 Definitions related to wood products

The supply of woody biomass for energy is intrinsically connected to the supply and transformation of wood for material use. Therefore, the analysis of woody biomass for energy must consider woody biomass used for all purposes, including wood products. Most definitions of wood products in this report depart from the terminology used in the Joint Forest Sector Questionnaire (Eurostat et al., 2017). The work required includes assembly of the different data sources, aggregation of some product categories and provision of estimates for some products (e.g. for black liquor). Therefore, the terminology used in this report can differ from the definitions used in the original data sources. The definitions below are the ones used in this report.

Removals consider the volume of all trees, living or dead, that are felled and removed from the forest, other wooded land or other felling sites. They include natural losses that are recovered (i.e. harvested), removals during the year of wood felled during an earlier period, removals of non-stem wood such as stumps and branches (where these are harvested) and removal of trees killed or damaged by natural causes (i.e. natural losses), e.g. fire, windblown, insects and diseases. It is important to note that this includes removals from all sources within the country including public, private, and informal sources. It excludes other non-woody biomass and any wood that is not removed, e.g. stumps, branches, and treetops (where these are not harvested) and felling residues (harvesting waste). Bark is usually excluded from the removal statistics.

Salvage loggings are any harvesting activity consisting of recovering timber that can still be used, at least in part, from lands affected by natural disturbances (source: EU 2013.); with natural disturbances denominating damages caused by any factor (biotic or abiotic) that adversely affects the vigour and productivity of the forest and that is not a direct result of human activities (FAO 2018). Salvage logging is part of the removals. It includes both the removal of dead trees (belonging to what is reported as natural losses) and living trees (part of the growing stock) to prevent the spread of diseases or pests.

Roundwood includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form (e.g. branches, roots, stumps and burls (where these are harvested)) and wood that is roughly shaped or pointed. It is a general term referring to wood fuel, including wood for charcoal and industrial roundwood. All roundwood is also referred to as primary wood or primary woody biomass.

Fuelwood is roundwood that will be used as fuel for energy purposes such as cooking, heating, or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel), round or split, and wood that will be used for the production of charcoal (e.g. in pit kilns and portable ovens), wood pellets and other agglomerates. It also includes wood chips to be used for fuel that are made directly (i.e. in the forest) from roundwood. It excludes wood charcoal, pellets, and other agglomerates.

Industrial roundwood corresponds to all roundwood except fuelwood. It includes sawlogs and veneer logs; pulpwood, round and split; and other industrial roundwood. As described in Chapter 3, industrial roundwood, although normally intended to be used for manufacturing of wood-based products, can sometimes end up as fuel.

Secondary woody biomass comprises all the woody biomass resulting from a previous processing in at least one industry. It includes solid by-products, like chips and particles, other by-products, like black liquor, bark and post-consumer wood.

One of the characteristics of woody biomass is that most by-products from harvest and transformation processes can be used for a few different purposes, augmenting the efficiency of the use of the biomass felled. Moreover, many wood-based products can be recycled or re-used at the end of their life cycle. To value these characteristics, we denominate and evaluate the cascade use of woody biomass. In this report, cascade use denominates the efficient utilisation of resources by using by-products and recycled materials for material use to extend total biomass availability within a given system (adapted from Vis el al. 2016).

These, and other terms related to wood products can be found in the glossary at the end of this report.

2.1.3 Definitions related to energy products

Solid biofuels cover organic, non-fossil material of biological origin which may be used as fuel for heat and electricity production. Note that for biofuels commodities, only the amounts specifically used for energy purposes are included in the energy statistics. Therefore, the non-energy use of biofuels is not taken into consideration and the quantities are null by definition.

Primary solid biofuels are defined as any plant matter used directly as fuel or converted into other forms before combustion. This covers a multitude of woody materials generated by industrial process or provided directly by forestry and agriculture (firewood, wood chips, bark, sawdust, shavings, chips, sulphite lye also known as black liquor, animal materials/wastes and other solid biofuels). This category excludes charcoal.

Wood pellets are agglomerates produced either directly by compression or by the addition of a binder in a proportion not exceeding 3% by weight. Such pellets are cylindrical, with a diameter not exceeding 25 mm and a length not exceeding 100 mm.

The term ‘other agglomerates’ is the term used for agglomerates that are not pellets, such as briquettes or log agglomerates. Wood pellets and other agglomerates are often reported jointly, with other agglomerates being usually a minor part.

Black liquor is a by-product from chemical and semi-chemical wood pulp industry.

These and other terms with referring to energy products can be found in the glossary at the end of this report.

2.2 Datasets on woody biomass and its use for energy

The use of woody biomass for energy takes place in a complex framework where the forest-based sector and its general dynamics is, in part, a supplier of energy in a policy context that aims to reduce the non-renewable energy use and the greenhouse gas emissions. To analyse these different aspects, various datasets must be used.

Figure 1 represents the complexity of the system and the main data sources, which are analysed in this section. Woody biomass for energy is one category of uses. The general energy statistics give information on the global energy mix including the use of biomass for energy. To some extent, greenhouse gases emitted from the burning of wood can be identified in the environmental accounts. These frame the scene from the uses side but do not allow for a good understanding of the relationships between these uses and management of forests and other ecosystems providing wood. The Joint Wood Energy Enquiry (JWEE) and the National Renewable Energy Action Plan (NREAP) progress reports detail the origin of the woody biomass, either directly from the forest or from forest-based industries. The JWEE also reports on the uses of wood for bioenergy and reconciles them with biomass sources. The Joint Forest Sector Questionnaire (JFSQ) makes it possible to link estimates of woody biomass used for energy to the sources of woody biomass, taking into account synergies and competition between energy and material uses. Finally, data released in Forest Europe, FAOSTAT and national forest inventories help evaluate the pressure on forest ecosystems resulting from the supply of primary sources of woody biomass. However, making these links between surveys is not straightforward, since surveys have different initial purposes, and therefore use diverse definitions and reporting units. We explain here how the data were harmonised to provide comprehensive information.

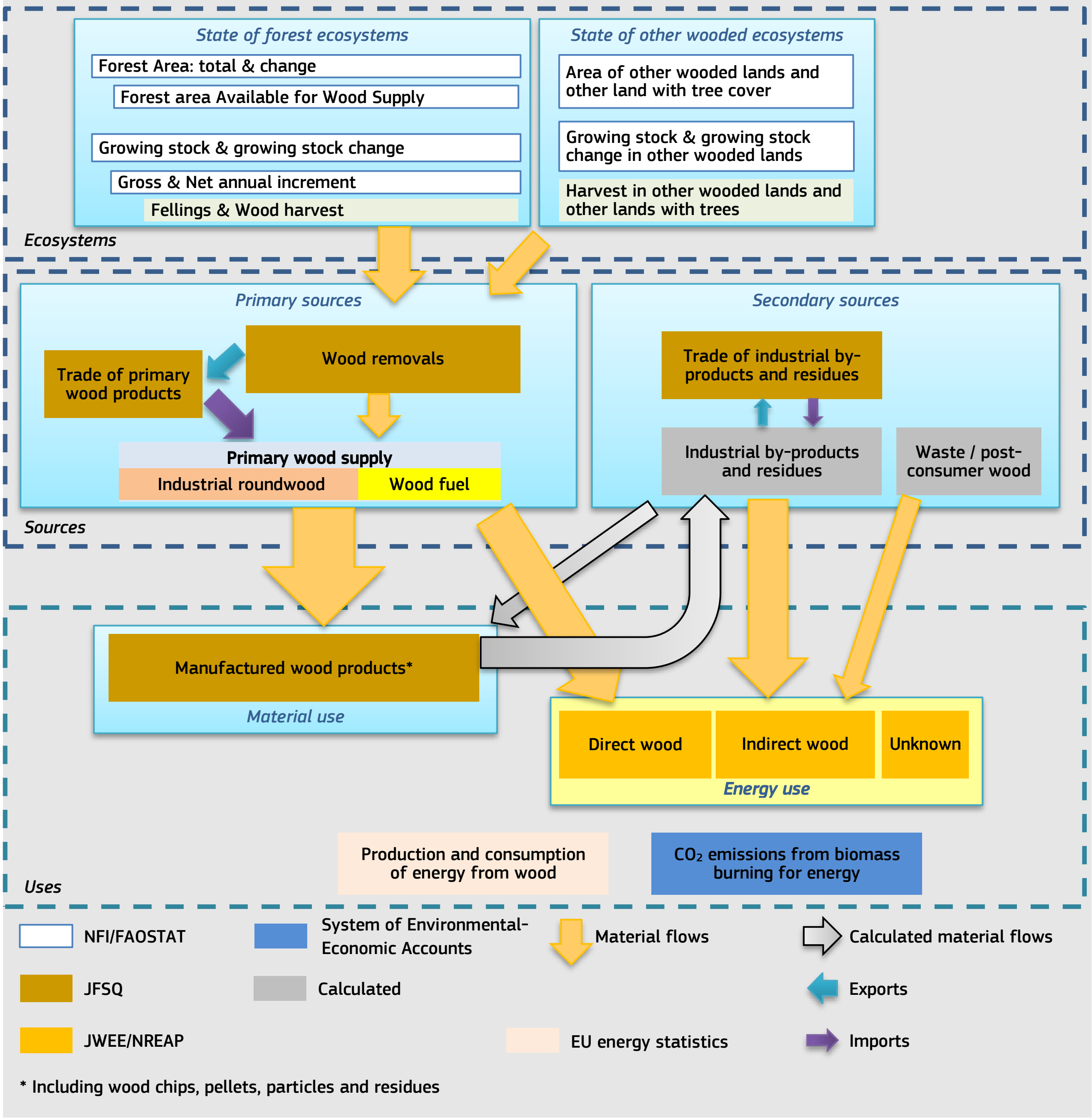

Figure 1. Combination of sources of information to analyse woody biomass for energy in the wood value chain

2.2.1 Information on forest ecosystems and their sustainable management

Forests in Europe are subject to a periodic review in the framework of Forest Europe, the brand name for the Ministerial Conference on the Protection of Forests in Europe (MCPFE) since 1990. The Liaison unit supports a large group of national and international experts who compute and analyse a set of 35 quantitative and 12 qualitative indicators. Out of the 35 quantitative indicators, 7 come from the Collaborative Forest Resources Questionnaire (CFRQ), led by FAO and used to prepare the Global Forest Resource assessment (FRA), 21 come from the Joint FOREST EUROPE/UNECE/FAO Questionnaire on Pan-European Quantitative Indicators for Sustainable Forest Management and 7 from international data providers (reporting original information or information from other enquiries such as the JWEE). Questionnaires answered by participating countries contain the indicators and explanations on how they are estimated. The latest database currently available are from the MCPFE 2015 (Forest Europe 2015), except for the CFRQ for which the 2020 results are published (FAO 2020). In preparation of the next Forest Europe ministerial conference in 2021 in Bratislava, a new State of Europe's Forests 2020 has been released showing the latest developments (Forest Europe, 2020). Quantitative indicators reported in Forest Europe are available from the Forest Europe database[4] (currently, data from the State of Europe's Forests 2015). Subsets of the information are also available from UNECE[5], FAO[6] and Eurostat[7].

Forest Europe gives access to a unique dataset covering the environmental, economic and social pillars of sustainability as well as the wood value chain from the primary production to the first transformation. Data reported in the questionnaires by national experts come from national forest inventories, statistical offices, national forest managers and administrations as well as international organisations. These data are often adjusted to cope with the differences in definitions, e.g. of forest and growing stock (Vidal et al. 2008), and reporting years.

Figures presented in the State of Europe's Forests (Forest Europe 2020) give an overview of the sustainable management of the Forests in Europe according to 6 criteria, briefly: status of forest resources, ecosystem health and vitality, production of wood, non-wood products and marketed services, biodiversity, protective function as well as other socioeconomic functions. The report presents indicators such as forest area, carbon stocks, growing stock by species, gross and net annual increments and fellings, as well as many attributes of forest diversity, their health status, their capacity to supply ecosystem services, including wood, non-wood forest products, marketed and some non-marketed services. The economic and social dimensions of sustainability are explored not only in forests, but also in the primary transformation sectors.

The State of Europe's Forests 2020 shows for example, that the use of roundwood increased in quantities and values from 1990 to 2015 with a slight inflection in the quantities around 2010 (indicator 3.2). However, this increase was observed on a limited number of countries offering time series for this indicator. An increase in wood fuel use (indicator 6.9: energy from wood resources) was reported between 2009 and 2013 as a major driver of the increase in roundwood uses in reporting countries. However, the EU coverage for this indicator does not exceed 51% of the total EU population.

Completeness of data is a major limiting factor for a detailed analysis of wood uses in the EU. For example, the felling rate (ratio between fellings and net annual increment considered one of the criteria for the evaluation of the sustainability of harvest[8]) is available for 24 EU countries for the year 2010, and only for 18 EU countries over the period 2000-2010. Moreover, even in the 2020 report, some data might be already outdated. For example, indicator 6.9 (energy for wood resources) was calculated based on a release of the Joint Wood Energy Enquiry that included data until 2015, to which 19 of the EU countries answered. The numbers in the State of Europe's Forests are used in this study to provide contextual information, but not to make detailed calculations.

In Europe, the primary sources of information on forests, their extent, their biodiversity and their capacity to supply wood are the National Forest Inventories (NFI) conducted by every EU member state (Tomppo et al. 2010). In each NFI, the list of attributes, definitions and methodology is adapted to the context of each country and its types of forests. Data are therefore not necessarily comparable. A number of recent efforts have been undertaken in Europe to

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[4] Forest Europe Database: https://foresteurope.org/state-europes-forests-2015-report/#1476295991324-493cec85-134b (accessed 4.1.2021)

[5] UNECE forest database https://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__26-TMSTAT1/ (accessed 1.12.2020)

[6] FRA database https://fra-data.fao.org/ (accessed 1.12.2020)

[7] https://ec.europa.eu/eurostat/web/forestry/data/database (accessed 1.12.2020)

[8] This number shall be typically below 100%. However, a felling rate above 100% is not considered as unstainable if because of exceptional fellings due to catastrophic events such as storms.

harmonise the data (see Chapter 4, Gschwantner et al. 2009; Alberdi et al. 2016; Gschwantner et al. 2019), and part of these efforts have been supported by JRC and integrated into this report. Unfortunately, so far, harmonised data are available for a limited number of variables. The area of forests and forests available for wood supply used to compute biomass available from forests, as well as for the assessment of the Net Annual Increment (NAI) in paragraph 3.2 are derived from the State of Europe's Forests 2015 (Forest Europe. 2015). On the other hand, the above ground woody biomass was estimated independently in the context of long-standing collaboration between JRC and NFI harmonising detailed national data. Further details on the collaboration with NFIs can be found in Chapter 4. To reconstruct the full data series and to derive the detailed breakdown of woody biomass categories, we also used modelling techniques such as those presented in Pilli et al. 2017.

The Forest Information System for Europe (FISE), although not directly used for this report, is mentioned here as it is becoming an important reference for forestry related data in Europe. FISE is being developed in a partnership among the services of the European Commission and the European Environment Agency (EEA). It is a unique repository of information on Europe's forests[9]. The FISE platform currently gives access and links to National level information, and National Forest Inventory data in particular, produced by the countries. It also links to international processes collecting or putting together data on forests such as the Global Forest Resources Assessments of FAO, Forest Europe, the European Forest Genetic Resources Programme, the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP-Forests), Global Forest Watch, and the European Forest Institute (EFI). FISE presents the data as they are with many details so that information can be used for research purposes and to inform policies with a good understanding of the state of knowledge and gaps. However, this source could not be used for this report because, in the current state, datasets lack harmonisation at the level of detail required to analyse the supply of woody biomass for energy use at the EU level.

2.2.2 Energy statistics and environmental accounts: contextual data

In the European Union, statistics on energy supply and use are collected by standard questionnaires according to Annex B of the Regulation (EC) No 1099/2008 of the European Parliament and of the Council of 22 October 2008 on energy statistics. Most estimates are reported in quantities of energy (such as Terajoules, TJ or tons of oil equivalent, toe). For solid biofuels, quantities are estimated using the net calorific value.

The table "Supply, transformation and consumption of renewables and wastes"[10] released by Eurostat provides data on indigenous production of energy from the categories "Fuelwood, wood residues and by-products" and "Wood pellets" respectively. Further, energy flows[11] are reported at an aggregated level under the category "Primary solid biofuels" that includes wood and black liquor as well as bagasse, animal waste, other vegetal materials and residuals and industrial waste. Because of their limited level of detail, these statistics can be used to contextualise the study, but they are not suitable to support the detailed analysis on biomass uses as pursued in the report.

The environmental accounts (United Nations 2014) make the link between the functioning of the economy, the consumption of energy, including bioenergy, and greenhouse gas emissions.

Physical energy flow accounts (PEFA) report flows of energy (including natural inputs used to manufacture energy products and energy residuals) from the environment into the economy, within the economy and from the economy to the environment. These accounts are compiled by

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[9] https://forest.eea.europa.eu/

[10] Table *nrg_cb_rw*: https://ec.europa.eu/eurostat/databrowser/view/nrg_cb_rw/default/table?lang=en

[11] Table *nrg_bal_sd*: https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_sd/default/table?lang=en

Member States and reported to Eurostat who calculate the accounts for the EU starting from 2014.

Air emissions accounts (AEA) record the emissions to the atmosphere of six greenhouse gases including CO_2 and Carbon dioxide from biomass used as a fuel (CO_2_Bio), and seven air pollutants. AEA offer breakdowns by 64 emitting industries plus households and a coverage consistent with the residency principle of national accounts. These accounts are also provided by member states to Eurostat.

The accounts make it possible to highlight the main users of wood, by-products and wood waste for energy. However, these datasets do not make it possible to identify the provenance of the woody biomass used for energy, nor the relation to the forest-based sector and sustainable forest management. For further details on the types of wood and wood products used for energy and the quantities at stake, additional information is needed.

2.2.3 Quantities and sources of woody biomass used for energy

The Joint Wood Energy Enquiry (JWEE) and the National Renewable Energy Action Plan (NREAP) progress reports provide information on the supply and use of woody biomass for energy estimated quantities (volume of weight).

The JWEE is an international survey collecting national statistics on wood energy sources and uses in UNECE countries. The UNECE/FAO Forestry and Timber Section collects and analyses the information in collaboration with the International Energy Agency (IEA), the Food and Agriculture Organization (FAO) and the European Commission (EC). Data have been collected every second year since 2007. The latest publicly available dataset are from the JWEE 2015. It includes answers from 32 countries, including 20 EU member states and the UK. As of March 2019, JWEE 2017 had been answered by 29 countries including 14 EU Member States. Data collection and control is still going on and data are therefore not available for this report.

In the JWEE, the energy use of woody biomass is reported by economic sector and by type of biomass. Numbers are typically reported in tons of dry matter except for liquid fuels (in tons). These are converted when needed into cubic metres and energy content using coefficients integrated in the JWEE form filled in by national experts. The JWEE also includes some information on the woody biomass sources imported from the Joint Forest Sector Questionnaire (JFSQ, see Section 2.2.4). Since not all EU member states answer the JWEE, complementary sources of information on wood energy are needed.

Because of the high level of detail requested in the JWEE questionnaire countries reply on various sources to answer it, leading to the use of different units. Country-specific conversion factors, provided by the respondents, are used to convert from the reporting original units to the common metric system. These conversion factors were not disclosed in the 2015 release. However, the results are also provided with a summarised format (the so-called ‘Country profiles’), that reports statistics, in cubic metres solid volume, aggregated by four categories of sources (Direct, Indirect, Recovered, Unspecified) and four categories of uses (Power and Heat, Industrial, Residential, Other), for all years for which information is available. This is the dataset that has been used to evaluate the Wood Resource Balances, further described in Chapter 3. As a voluntary exercise, the JWEE cannot provide the complete picture of the UNECE region, or of the EU (see Table 1). We looked to the progress reports that all EU Member States are obliged to submit regarding the National Renewable Energy Action Plans (NREAP) as a supplementary source of data for wood energy.

All EU Member States (MS) submit a NREAP progress report as required by article 4 of the Renewable Energy Directive 2009/28/EC of 23 April 2009 on renewable energies. Each progress report provides a detailed roadmap of how the MS expects to reach its legally binding 2020 target for the share of renewable energy in their total energy consumption. Every second year, they provide details on the actual amount of energy provided by renewable sources for all the years. In particular, Member States are asked to give an estimate of, the supply of woody biomass for energy uses by category (Direct, Indirect, Domestic, Imported) in cubic metres.

These NREAP progress reports cover all EU Member States and all years while the JWEE contains information for fewer countries and only for odd years (Table 1). However, NREAP progress reports provide insufficient information to analyse the use of woody biomass for energy in detail. Moreover, the suggested template is not always strictly followed by the MS, so heterogeneous definitions are adopted, and frequent problems with unit conversions arise. When feasible, we have tried to account for the short rotation coppices, which are reported as a separate item.

It is worth to note that JWEE and NREAP data, when simultaneously available, show non-negligible differences, up to some million m^3 at country level.

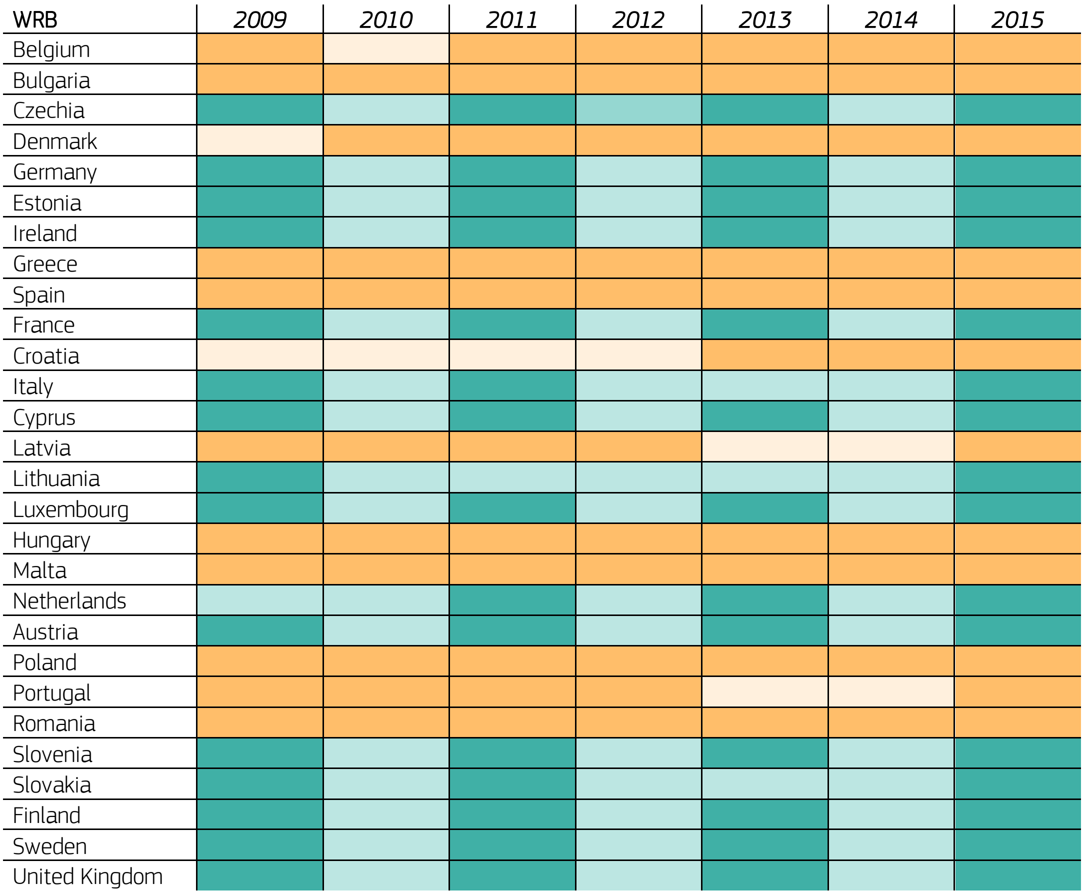
Table 1. Availability of JWEE (green), NREAP (orange) data usable to analyse energy from woody biomass for the EU-27 member states and the UK.

JWEE 🟩 **NREAP** 🟧	***2009***	***2010***	***2011***	***2012***	***2013***	***2014***	***2015***
Austria	🟩 🟧		🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧
Belgium	🟩 🟧		🟧	🟧	🟧	🟧	🟧
Bulgaria	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Croatia					🟧	🟧	🟧
Cyprus	🟩 🟧	🟧	🟩 🟧	🟧	🟩		🟩 🟧
Czechia	🟩		🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧
Denmark		🟧	🟩 🟧	🟧	🟩 🟧	🟧	🟧
Estonia	🟩 🟧	🟧	🟩 🟧	🟧	🟩		🟩 🟧
Finland	🟩		🟩 🟧	🟧	🟩 🟧	🟧	🟩
France	🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧
Germany	🟩		🟩		🟩		🟩 🟧
Greece	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Hungary	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Ireland	🟩 🟧	🟧	🟩 🟧	🟧	🟩		🟩 🟧
Italy	🟩 🟧	🟧	🟩 🟧	🟧	🟧	🟧	🟩 🟧
Latvia	🟧	🟧	🟧	🟧			🟩 🟧
Lithuania	🟩						🟩 🟧
Luxembourg	🟩		🟩		🟩		🟩
Malta	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Netherlands			🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧
Poland	🟧	🟧	🟩 🟧	🟧	🟧	🟧	🟩 🟧
Portugal	🟧	🟧	🟧	🟧			🟩 🟧
Romania	🟧	🟧	🟩 🟧	🟧	🟧	🟧	🟧
Slovakia	🟩 🟧	🟧	🟩 🟧	🟧	🟧	🟧	🟩 🟧
Slovenia	🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧
Spain	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Sweden	🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧	🟧	🟩 🟧
United Kingdom	🟩 🟧	🟧	🟩 🟧	🟧	🟩		🟩

The decision on what dataset to use (see Table 2) for each MS was based on the following decision rules:

- Use of only one energy data source for the same country in different years;
- Clear preference given to the JWEE, when available, because of the harmonised units and definitions as well as the higher level of details;
- Possibility to interpolate the time series, preferring short data gaps;
- Availability of conversion factors to harmonise the data from the NREAP progress report;
- Results that lead to the lowest imbalance in Wood Resource Balances (WRB).

Table 2. Energy data sources for the WRBs (dark green: JWEE, light green: interpolation between JWEE values, orange: NREAP data, light orange: interpolation of NREAP data).



WRB	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Belgium	🟧	🟨	🟧	🟧	🟧	🟧	🟧
Bulgaria	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Czechia	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Denmark	🟨	🟧	🟧	🟧	🟧	🟧	🟧
Germany	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Estonia	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Ireland	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Greece	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Spain	🟧	🟧	🟧	🟧	🟧	🟧	🟧
France	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Croatia	🟨	🟨	🟨	🟨	🟧	🟧	🟧
Italy	🟩	🟢	🟩	🟢	🟢	🟢	🟩
Cyprus	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Latvia	🟧	🟧	🟧	🟧	🟨	🟨	🟧
Lithuania	🟩	🟢	🟢	🟢	🟢	🟢	🟩
Luxembourg	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Hungary	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Malta	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Netherlands	🟢	🟢	🟩	🟢	🟩	🟢	🟩
Austria	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Poland	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Portugal	🟧	🟧	🟧	🟧	🟨	🟨	🟧
Romania	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Slovenia	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Slovakia	🟩	🟢	🟩	🟢	🟢	🟢	🟩
Finland	🟩	🟢	🟩	🟢	🟩	🟢	🟩
Sweden	🟩	🟢	🟩	🟢	🟩	🟢	🟩
United Kingdom	🟩	🟢	🟩	🟢	🟩	🟢	🟩

Since the JWEE is biennial, a value for even years was estimated using linear interpolation (see the example for Slovenia in Figure 2). This technique was also used when data was missing for some years (e.g. in Latvia, Lithuania or Italy, see Table 2).

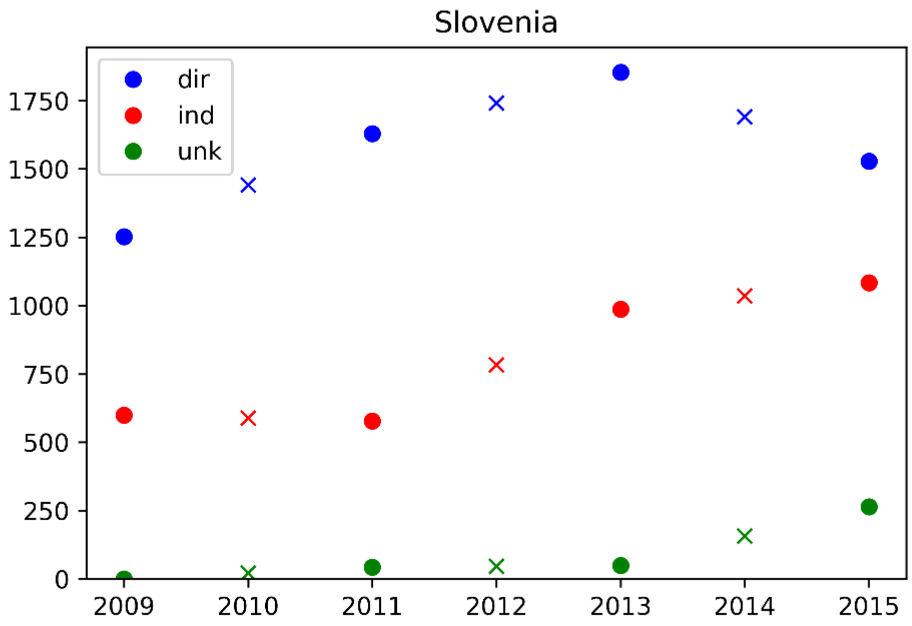


Figure 2. Example of data interpolation for Slovenia. Points correspond to JWEE figures, crosses represent interpolated figures. Unit: thousand m^3 solid volume (dir: direct/primary wood, ind: indirect/secondary woody biomass, unk: unknown kind of woody biomass).

Based on what is presented above, it is clear that the available data are far from comprehensive. There are various sources for error, notably inconsistent and incomplete data reporting. When moving to an analysis at the EU scale, some of these errors are cumulative, in particular the errors associated to underreporting. This effect is not always detected through the Wood Resource Balance (WRB) analysis described in Chapter 3, because underreporting in sources can have a counterpart in underreported uses. This is evident from the country-level WRBs where some countries report quantities of uses that are smaller than quantities of sources.

2.2.4 Production and trade of roundwood and wood products

The most detailed source at the European level to describe the primary supply of wood and its primary transformation is the Joint Forest Sector Questionnaire (JFSQ). This questionnaire is defined, collected and analysed by four partner organisations: the United Nations Economic Commission for Europe (UNECE), the Food and Agriculture Organisation of the United Nations (FAO), Eurostat, and the International Tropical Timber Organization (ITTO), under the coordination of the inter-secretariat Working Group on Forest Sector Statistics. The JFSQ is an annual survey detailing roundwood removals and trade as well as production and trade of wood products and by-products.

Most of the information are supplied from governments in the form of replies to questionnaires. In certain cases, the measurement units used by Member States differs from those of the JFSQ. Coefficients used to convert volumes and mass (weight) to comply with the JFSQ are shown in the questionnaire itself. In all JFSQ releases, the dataset also includes data obtained from sources beyond the official replies to questionnaires and estimates made by FAO. Since these estimates are based on other information, models and assumptions, the figures published may change from one release to another. One of the areas where statistics are not reported very often by countries is fuelwood. So, for many countries, fuelwood production given by the JFSQ is an estimate, based on a model of fuelwood consumption. This estimate changed quite noticeably between the 2017 release used to calculate the WRBs and the 2020 release currently available.

Most products are not reported in mass, but in different units, ranging from cubic metres solid volume under bark for roundwood to metric tonnes air-dry weight for wood pulp. Conversion factors are used to make the numbers comparable. Estimates of wood pellet production were not available from the JFSQ for the years prior to 2012. These quantities were taken from Eurostat data (table FOR_BASIC[12]) for the missing years when calculating the WRBs that are described in Chapter 3.

Moreover, industries manufacturing wood products usually report the quantities of their production, which exclude the processing residues, and includes some non-wood materials (such as glue). Therefore, input/output coefficients for the primary products are applied (EC-JRC 2010). In Chapter 3, all numbers related to WRB analysis are reported in solid wood equivalent (SWE). This unit, corresponding to the effective volume (in cubic meters) of wood that is transferred between sectors, is the most appropriate to calculate a wood resource balance in which supply quantities are comparable to use quantities. Compared to other traditional units such as the roundwood equivalent (quantity of roundwood necessary to produce one unit of a product), the SWE is usable to analyse cascading value-chains, where by-products of a sector are inputs to other sectors.

As discussed in Jonsson et al. (2020), analysis of the three main data sources (JFSQ, JWEE and NREAP progress reports) indicates notable inconsistencies in the data. Resulting uncertainty calls for providing a range of possible values.

2.3 Conclusions and key messages

This analysis shows that numerous data sources can be used to analyse the supply and use of wood for energy as well as their relation to forest management in the environmental impact. However, most datasets are incomplete or provide insufficient detail. Because of the diversity of data providers, the scope of the studies and the units in use, results do not always appear coherent, thus requiring a deep crosscheck of the statistics prior to use.

The units of reporting differ between products and reporting questionnaires. Therefore, numerous conversion factors must be used. The conversion is a source of uncertainty in the results. Moreover, statistics on wood energy supply and use face large data gaps. These gaps must be filled by cross calculations and assumptions. The total uncertainty cannot be estimated statistically because of the complexity of the estimation framework and the lack of information on the uncertainty of the input data. Nevertheless, a specific effort was made to give ranges of possible values in Chapter 3.

As of December 2020, an updated version of the JWEE dataset was released. It provides recent information (latest year: 2017) on the use of woody biomass for energy. Unfortunately, this release came too late to be used in this report. Moreover, as for other releases, it covers only part of the EU and several crosschecks are needed to ensure the reliability and comparability between the data sources. A major progress concerning the completeness of the data and the coherence is expected under the Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action[13]. This Regulation defines how every EU Member State shall report to the Commission, every second year from March 2023, on the status of implementation of its integrated national energy and climate plan. These reports will cover the main energy aspects among which of greenhouse gas emissions and renewable energies and trade. In addition to the integrated vision, the definition of the reporting items and units in Annex IX of this Regulation will favour a structured and consistent reporting with harmonised and complete data, although some fields remain optional. A complete, timely and quality checked reporting would certainly help properly monitoring the bioenergy sector and the bioeconomy in general (Robert et al. 2020) and support further analysis as the ones described in this report.

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[12] https://ec.europa.eu/eurostat/databrowser/bookmark/11803c63-10c8-488c-8391-75df9ad8af0d?lang=en

[13] http://data.europa.eu/eli/reg/2018/1999/oj/eng

Key messages:

- Statistics on sources and uses of woody biomass for energy are found in numerous reporting schemes with different scope, coverage, aggregation levels, completeness and reporting units.
- Numerous data sources can (and must) be used for a comprehensive coverage of supply and use of wood for energy in the EU because no one source provides a full picture.
- The need to integrate different data sources carries considerations regarding consistency across datasets, data transformation and harmonisation, and data integrity, increasing the uncertainty of the assessments.
- Expert knowledge is needed to collate and interpret the different data sources.
- Despite the abundance of available datasets, large data gaps exist.
- Data provided under the Governance of the Energy Union Regulation as of 2023, will improve the data quality and may positively impact the coherence between the three main data sources (JFSQ, JWEE and NREAP progress reports) used to quantify woody biomass used for bioenergy.

3 Woody biomass for energy

3.1 Woody biomass in the forest-based bioeconomy

Analysing the economy based on woody biomass, in particular the energy production, is quite a complex task. The forest-based industries and the energy production sector are intricately interlinked, displaying synergies as well as competition (see Cazzaniga et al. 2019a). Sawmilling by-products are used for wood pulp (for paper as well as textile fibres) and wood-based panels manufacturing as well as for energy production (see, e.g., Jonsson & Rinaldi 2017), while side-streams from chemical pulping are used in the chemical industry as well as for energy production (see Hurmekoski et al. 2018). The demand (and thus price) for sawlogs is one of the most determinant factors for the supply of primary woody biomass, including woody biomass for energy (see, e.g., Camia et al. 2018). The supply of primary woody biomass might also be affected by natural disturbances. Energy and material use (mainly wood-based panels but also wood pulp manufacturing, in most cases not sawmilling, as the price of saw logs is too high) also compete for primary sources (removals) of woody biomass (see, e.g., Jonsson & Rinaldi 2017). This means that developments in wood-based product markets are instrumental to the supply of woody biomass for energy purposes, and thus an assessment of sources and uses of woody biomass for energy needs to also consider forest-based industries.

Some major ongoing trends affecting EU forest-based industries are the substitution of electronic information and communication technology (ICT) for printed media resulting in a decreased demand for graphic paper, while growing trade and e-commerce have instead increased the demand for packaging paper. Performance-based common construction standards for Europe (EU 2011), the introduction of engineered wood products (EWP), and prefabrication have boosted the competitiveness of wood in large-scale construction projects (Hurmekoski et al. 2015). Important developments currently affecting EU forest-based industries include natural disturbances and the ensuing salvage logging, which leads to a temporary oversupply of primary woody biomass (see section 3.3), and the COVID-19 pandemic, whose full effect on the demand for wood-based products is yet difficult to discern.

3.2 EU[14] Forest resources and forest management

Forests provide a wide range of ecosystem services, such as carbon storage and sequestration, habitat provision, water regulation (quality, quantity, flow), regulation of air quality, soil erosion control, recreation, wood and non-wood products. The EU, together with the countries signatories of the Ministerial Conference for the Protection of Forests in Europe (Forest Europe)[15] has endorsed the Principles of Sustainable Forest Management as laid down in the Forest Europe declarations. Furthermore, provisions are in place in all EU MS, aimed at safeguarding the sustainability of forest management.

The total forest area of the EU has expanded steadily since 1990 (Figure 3). In 2020, in the EU-27, it amounted to 159 million hectares (Mha), or 39.8% of the total land area (computed from dataset in FAO 2020)[16].

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[14] The years assessed were prior to Brexit. 'The EU' corresponds to EU-27 + UK unless otherwise specified

[15] https://foresteurope.org/

[16] The State of Europe's Forest 2020 (SoEF2020) of Forest Europe, was published during the latest stages of preparation of this report. For this reason, direct reference to its data is limited.

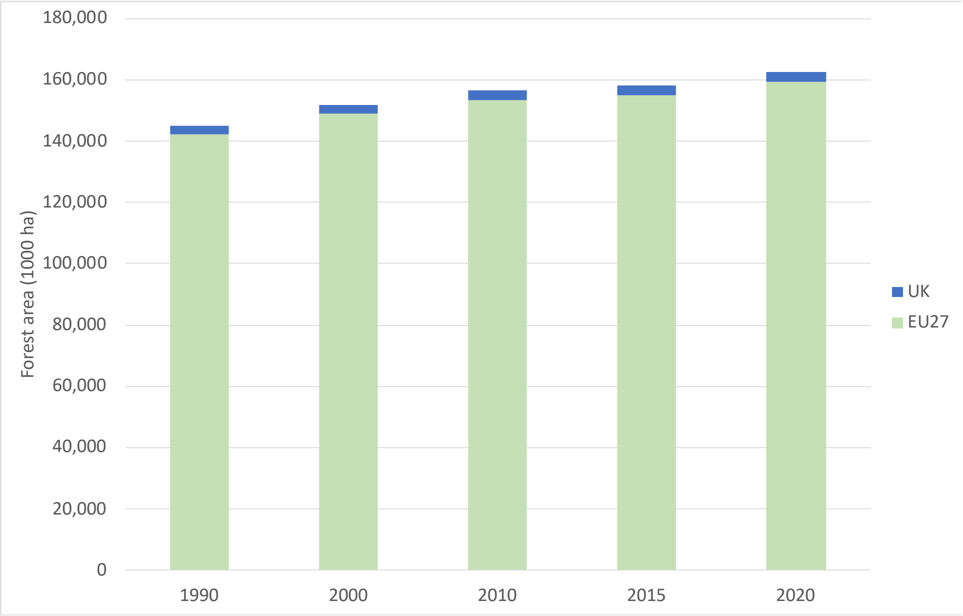

Figure 3. Forest area evolution in the EU. Source: FRA 2020 (FAO 2020)

There is a considerable variation in growth conditions, tree species composition and diversity as well as management practices and intensity in EU forests. A management practice particularly important for bioenergy, especially in Southern Europe, is the coppice system, amongst the oldest form of forest management developed to supply rural communities and early industries with wood, mainly for energy (Unrau et al. 2018). Following the findings of the COST Action EuroCoppice (FP1301)[17], coppice forests cover more than 19 Mha in the EU, corresponding to about 12% of the total forest area in 2015. The large majority (17 Mha) are in the EU Mediterranean countries, where about 32% of the forest area is reported as coppice (Unrau et al. 2018).

In what follows we present an overview regarding increment and fellings in EU forests, based on data reported in Camia et al. (2018). The average net annual increment (NAI) of stemwood (the stemwood produced in the forest annually minus losses due to natural mortality of trees) in the EU for the period 2004-2013 was some 759 million m^3 (Mm^3). The average NAI of the total above ground biomass in FAWS, which means adding the net annual increment of other wood components (OWC) such as treetops, branches, etc., was some 965 Mm^3. The NAI indicates the amount of woody biomass added to the growing stock per year. If the harvested living woody biomass exceeds the NAI, leading to a harvest to increment ratio higher than one, the stock of living woody biomass will decrease.

To assess the Gross Annual Increment (GAI) we estimated natural mortality using modelling as described in Pilli et al. (2017). Mortality refers to the death of forest trees due to the natural turnover rate, thus excluding disturbances such as wildfires or storms. GAI was estimated summing natural mortality and NAI.

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[17] https://www.eurocoppice.uni-freiburg.de/

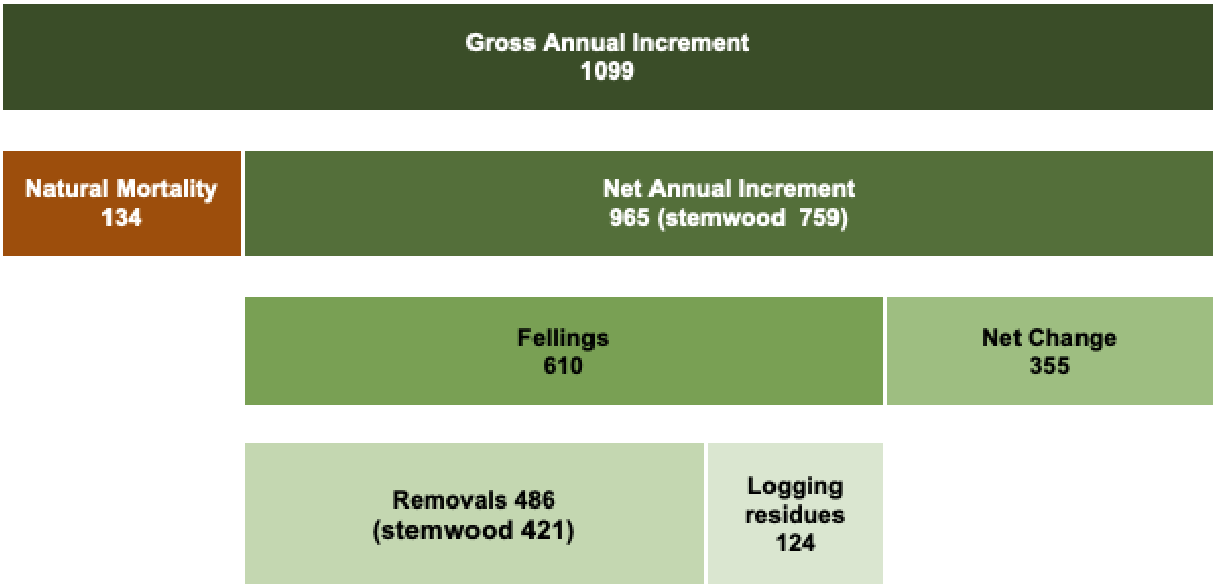

Figure 4. Increment, fellings and removals in the EU forest area available for wood supply; average values in Mm^3/yr for the period 2004-2013. Source: Camia et al. 2018

Only part of the biomass from felled trees is removed from forests during harvest operations, on average around 80 percent for the EU as a whole during the period 2004 to 2013 (estimate also based on Pilli et al. 2017). The remainder is left as logging (primary) residues. Leaving some biomass as residue on the ground after harvesting can be beneficial as it will constitute soil organic matter and nutrients, influence competing vegetation and soil microclimate, and it will affect in turn soil physical properties, soil carbon content and future forest productivity. Removing brush piles that may serve as habitats may adversely affect biodiversity. However, effects are highly variable and site-dependent, thus limiting the possibility to make generalised conclusions about potential impacts. For example, in fire prone areas a more intense removal of residues can at times constitute a positive management practice, since it reduces the fuel load thus lowering fire hazard. Potential impacts of the removal of residues are discussed further in Chapter 5.

Elaborating the wood removals reported by Eurostat with allometric models and literature findings (e.g. Pilli et al. 2017) we estimated that, during the 10 years considered, on average 610 Mm^3 were felled each year, of which 486 Mm^3 were removed, while 124 Mm^3, i.e., 20%, were left in the forest as logging residues. Removals comprise 421 Mm^3 stemwood (87%) and 65 Mm^3 OWC (13%).

The NAI that is not felled corresponds to the net annual change in living biomass in EU forests and equals 355 Mm^3. A small fraction of removals is also made of dead wood (thus affecting the natural mortality block), but we do not have sufficient data to provide an estimate.

Figure 5 depicts estimates of NAI, removals, and felling in EU FAWS. Comparison of the red dotted line (NAI of total woody biomass) with the full bars (fellings or harvests) gives an idea about the biomass stock balance resulting from forest management. It appears that fellings, as EU average, have been consistently lower than NAI over the period in question.

The NAI per hectare in the EU has been slightly declining since 2000 (Camia et al. 2017), as also observed by various authors (Nabuurs et al. 2013; Pilli at al. 2017). Such trend has been attributed to a combination of ageing EU forests and high stock volumes per hectare.

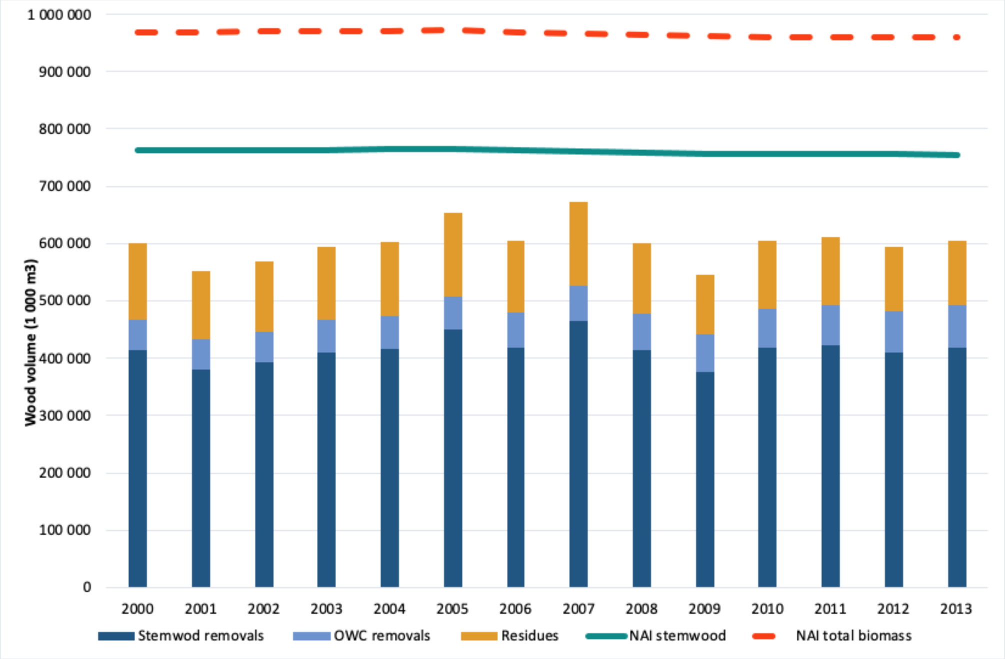

Figure 5. Net annual increment, removals, and fellings in the EU FAWS. Source: Camia et al. 2018

As mentioned earlier, this overview is based on published sources. However, it is important to recall that removals and fellings statistics are subject to high uncertainties (see, e.g., Pilli et al. 2015, Jochem et al. 2015). Consequently, we have analysed in detail the woody biomass flows and assessed the ranges of possible adjusted figures for the EU. The analysis and corresponding results are reported in section 3.5.

Natural disturbances also play an important role in affecting both NAI and removals (salvage loggings), as discussed in section 3.3.

3.3 Natural disturbances and wood supply

As described later in this chapter, the supply of primary wood for material as well as for energy use has increased in recent years. The wood resource balance (section 3.5, Table 4) indicates that domestic primary wood supply increased by 18%, from 442 Mm^3 in 2009 to 522 Mm^3 in 2015. However, it should be noted that demand of wood for material was at a periodic low in 2009, following the financial crisis of 2007-2008 and the ensuing economic crisis. Thus, as recovery started, demand and supply of wood has increased. Part of this increase might also be due to rising intensity and frequency of natural disturbances. This section is therefore dedicated to understanding how natural disturbances, followed by salvage loggings in the EU, can affect primary wood supply in the forest-based sector.

European forests are threatened by natural disturbances caused by abiotic and biotic agents such as windstorms, droughts, fires, insect outbreaks or combination of these agents, some of which are exacerbated by climate change. Natural disturbances have an effect on forest ecosystem services in different ways (Thom and Seidl, 2016). For instance, positive impacts may be registered for biodiversity, such as creating keystone habitats within forested landscapes while negative impacts may be registered for carbon storage. Forest disturbances are a natural process of forest dynamics. There is evidence that forest disturbances happened hundreds of years ago in Europe's forests (Schurman et al., 2018). However, the rising intensity and frequency of these disturbances are mainly due to the changing climate and a long history of human activities in the forests. It should be noted that, as detailed in Forzieri et al. 2020, vulnerability of the forest to natural disturbances is determined by forest structural properties, climate and landscape factors, agent of natural disturbances, etc.

It is estimated that in Europe over the period 1950-2000, an annual average of 35 million m^3 of wood, which is 8.1% of the total fellings, was damaged mainly by the windstorms and bark beetles with high variation between years (Schelhaas et al., 2003) and among countries. In 2018 this figure is over 100 million m^3 in 17 Member States (Figure 6). Thus, natural disturbances have dramatically increased in Europe in the last forty years, especially during the first decade of the twenty-first century (insect outbreaks +602%, wildfires +231% and windstorms +140% relative to 1971–1980) (Seidl et al., 2014) and it is expected that natural disturbances will be more frequent and intensive due to climate change in the future (Seidl et al., 2017). Climate change will modify forest structure and dynamics through direct (precipitation, temperature, droughts) and indirect (disturbance) effects, which will affect wood production, carbon storage and other ecosystem services (Lindner et al. 2014; Senf et al., 2020).

Salvage logging is a common practice and in many EU countries mandatory practice to remove damaged wood after a disturbance in order to minimise losses and, where applicable, to prevent the spread of pests and disease to the remaining forest (e.g., bark beetles). After wind or snowstorms, the damaged logs tend to degrade rapidly due to insects and other pathogens, therefore salvage logging is often performed in the weeks following the disturbance although, in case of large events, it may take years to be completed. In the case of a large-scale disturbance, salvage logging produces a significant amount of wood of various qualities (damaged, infected, rotten, broken, split) within a very short time on the market. Damaged wood is usually used for energy generation, wood pulp, and wood-based panels manufacturing. For sawmilling, only undamaged roundwood is used. An increased supply of woody biomass in the short time might distort the market by reducing wood prices and switching woody biomass flows for energy (from harvest residues to chipped logs). When markets become flooded with wood, prices collapse (Holmes, 1991). For example, in Czechia wood prices decreased to one fourth in response to the massive bark beetle outbreak in 2018 compared to average wood price in 2011–2017 (Hlásny et al., 2019). The effect of natural disturbances on the wood market varies greatly from local to global scales (including international trade), and from short-term to long-term effects (Hlásny et al., 2019). For example, the bark beetle outbreak in Belarus in 2018 increased export of secondary wood products (e.g. wood chips and particles) by three times compared to export quantities in 2015 (FAOSTAT, 2020). The export was mainly to the Baltic States, resulting in oversupply of energy wood and a decrease in prices below production costs. At the same time, significant increase in export of EU roundwood to China is observed. According to the UN trade statistics in 2019 export of EU roundwood to China increased by ten times compared to export quantities in 2015, from 2.1 million m^3 to 21 million m^3 respectively, mainly from Belgium, Czechia and Germany (United Nations, 2020). This might be due to oversupply, decreased wood prices and limited wood industry capacity in the EU.

To estimate the effects of natural disturbances and draw conclusions, data on salvage loggings are needed, however, currently there is no common dataset on salvage forest loggings in the EU. The European Commission[18] has therefore initiated a data-collection process for the period 2004-2019. Data on total harvest, salvage loggings and causes of salvage loggings were collected in 17 Member States by searching publicly available national datasets, reports, Eurostat and/or consulting with national experts.

Data on salvage loggings were found in the following Member States: Austria, Bulgaria, Croatia, Cyprus, Czechia, Estonia, France, Finland, Germany, Hungary, Latvia, Lithuania, Romania, Poland, Slovakia, Slovenia and Sweden. These Member States represent 76% of total forest area in EU-27. In the remaining Member States, data on salvage loggings are not available. Most of the countries report salvage loggings under bark, but some countries report over bark. For

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[18] The Directorate General for Agriculture of the European Commission

comparison reasons data were converted to under bark by using forest product conversion factors (FAO 2020b). In Poland data on salvage loggings are collected in the state forests only that represent 80% of the forest area in the country, therefore salvage loggings were upscaled to the country level.

It is important to note that the time series where annual data on salvage loggings are available varies among Member States. In some countries data are available for the entire period requested 2004-2019, but in others, data are available for a shorter period. For the period 2014-2018, data are available in all 17 Member States in which data were collected. Figure 6 shows the time series of salvage loggings, overlapped with the graphic of total removals in seventeen Member States for the period 2014-2018. The time series of total removals and salvage loggings for the period where annual data on salvage loggings are available is shown in Figure 7 for each of the 17 Member States.

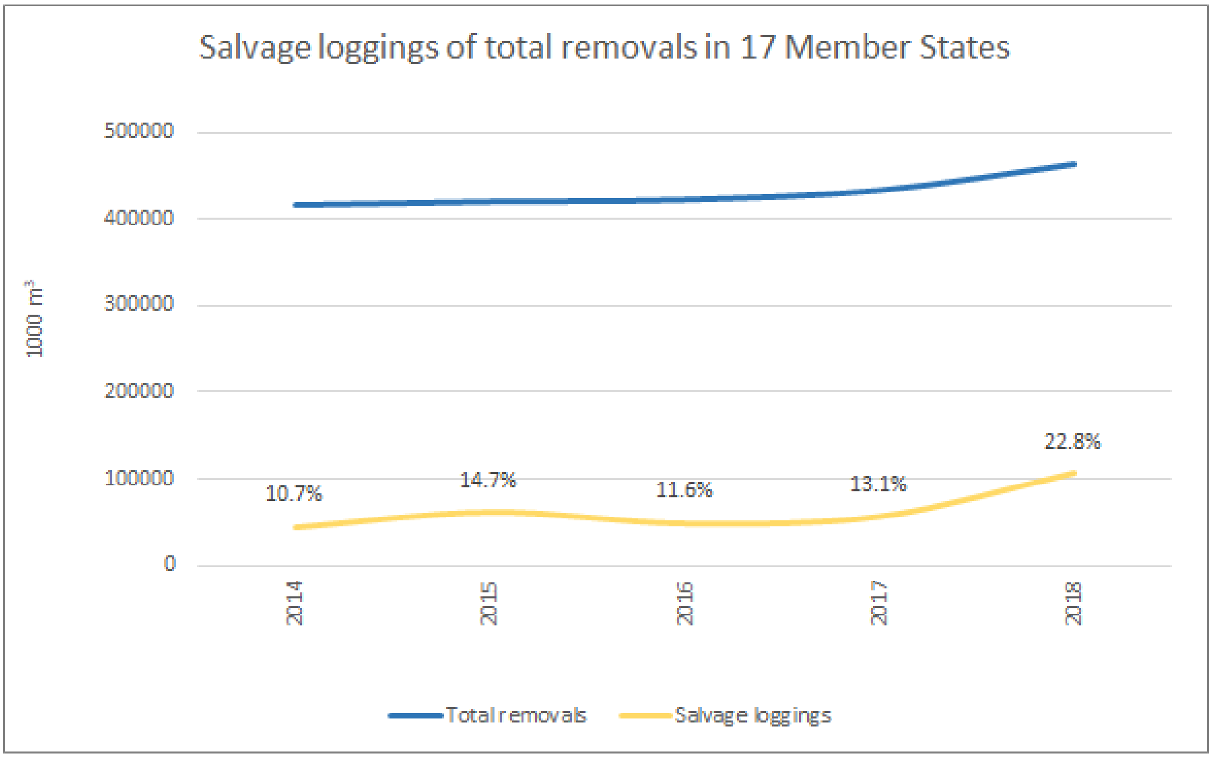
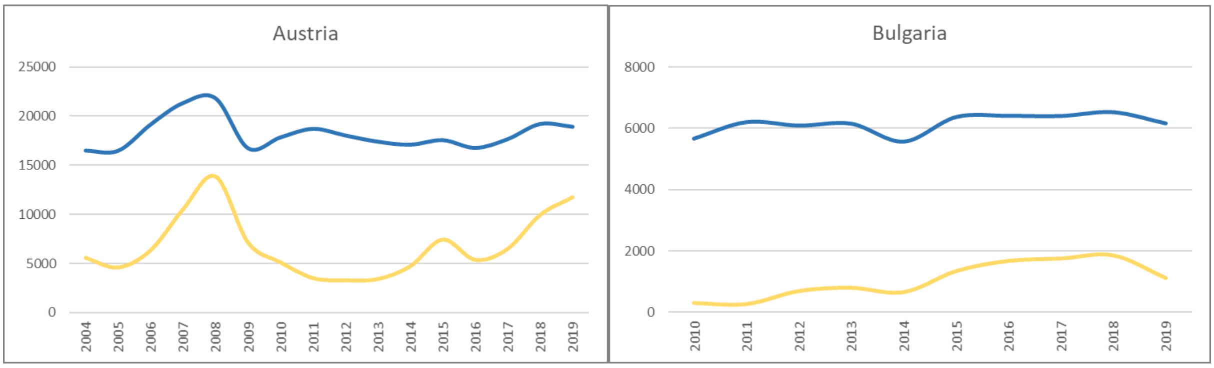
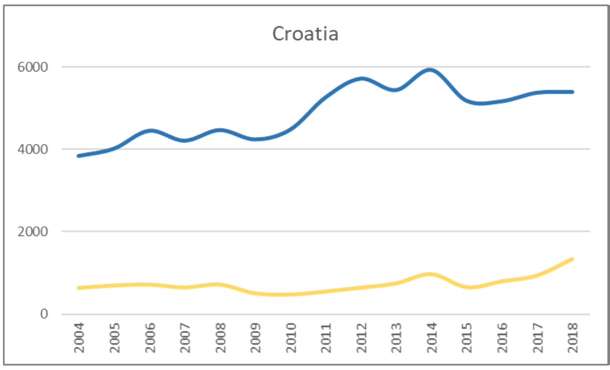


Figure 6. Salvage loggings of total removals (1000 m^3, u.b.) in 17 Member States; for the period 2014-2018.




Croatia
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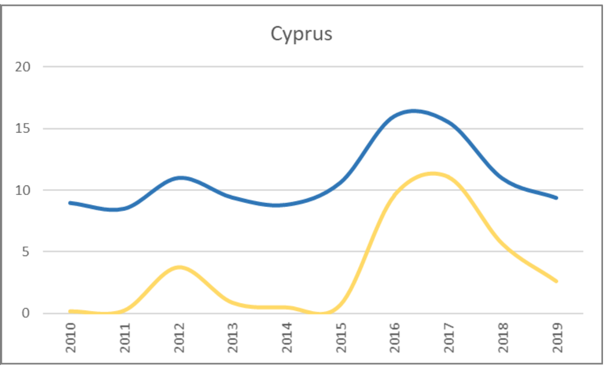
Cyprus
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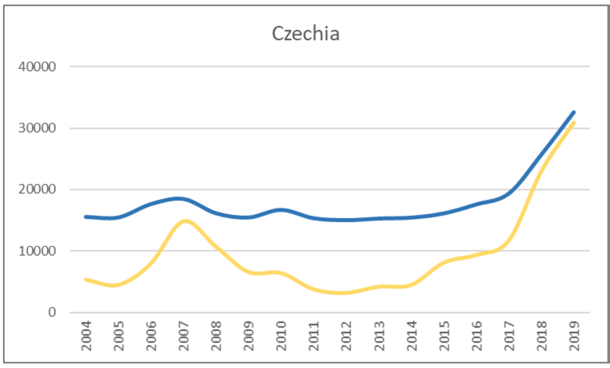
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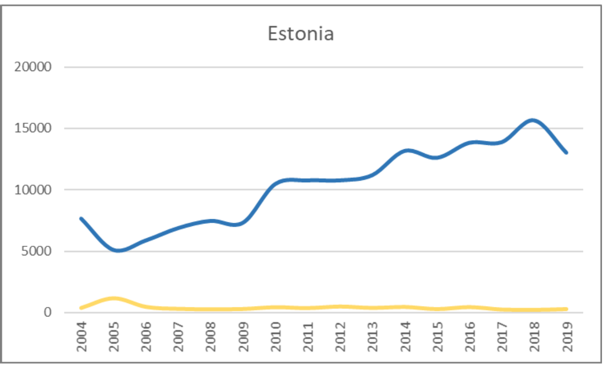
Estonia
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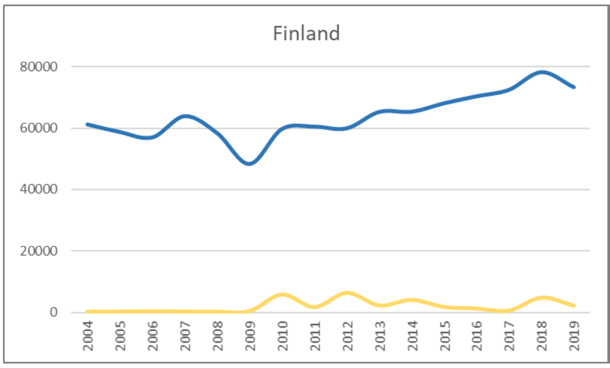
Finland
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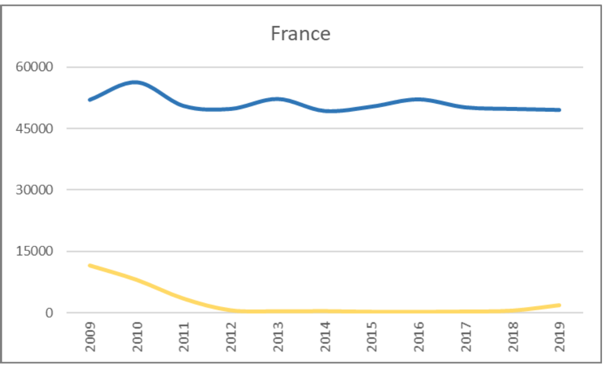
France
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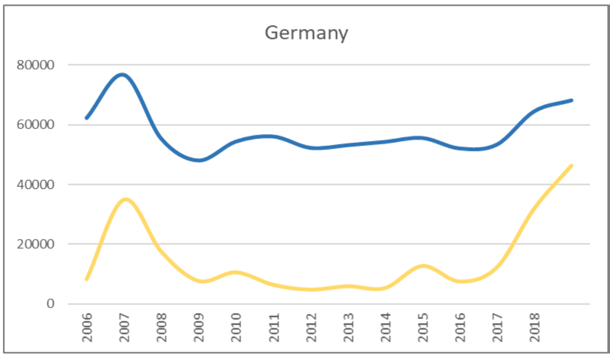
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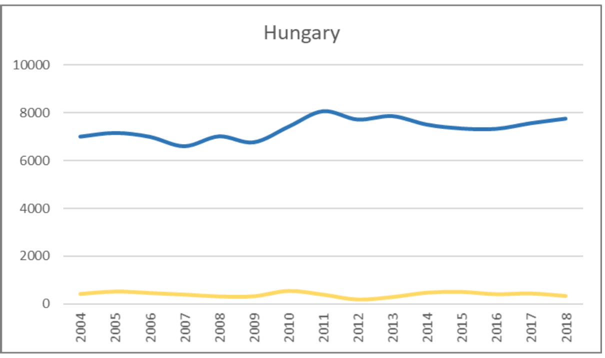
Hungary
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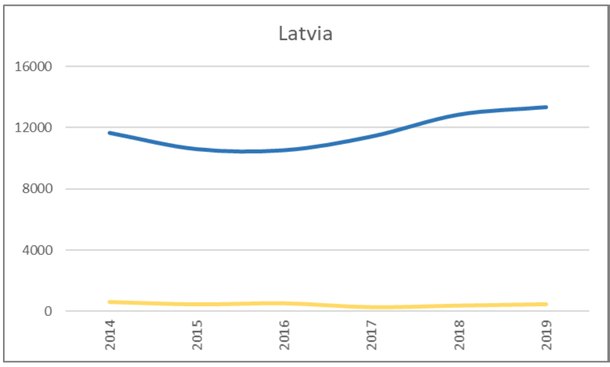
Latvia
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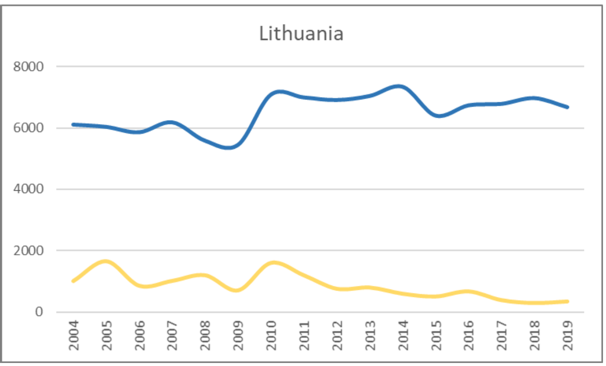
Lithuania
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Figure 7. Time series of salvage loggings and total removals (1000 m^3, u.b.) in 17 Member States, where annual data on salvage loggings are available. Blue lines represent total removals, yellow lines represent salvage loggings.

In ten countries (Austria, Cyprus, Czechia, Finland, Germany, Lithuania, Poland, Slovakia, Slovenia and Sweden) data on causes of salvage loggings are available for their respective time periods. Table 3 shows marked annual variation in causes. The attribution to different causes also varies among Member States. For instance, salvage loggings due to insect damage in Poland is attributed to 'other causes', while in Cyprus 'other causes' infers forest fires.

Table 3. Share of salvage loggings by causes over the reported period.

Member State	Reported period	Causes of salvage loggings over reported period		
		Wind (%)	Insects (%)	Other (%)
Austria	2004-2019	43	37	20
Cyprus	2010-2019	0	0	100
Czechia	2004-2019	47	41	12
Finland	2004-2019	74	8	18
Germany	2006-2019	49	38	13
Lithuania	2004-2019	60	28	12
Poland	2009-2019	59	0	41
Slovakia	2004-2019	44	49	7
Slovenia	2004-2019	21	40	39
Sweden	2004-2018	94	3	3

This data analysis focusses on understating how natural disturbances in the EU can affect primary wood supply to the forest-based industry. Our data indicates that natural disturbances mainly caused by wind and insects and followed by salvage loggings have increased during the time period considered, especially in Central Europe, confirming the increasing trend of natural disturbances reported in the literature (Seidl et al., 2014; Gregow et al., 2017; Kulakowski et al., 2017). In the 17 Member States that data were analysed, salvage loggings in 2018 increased by 138 % compared to 2014, from 44.5 million m^3 to 106 million m^3 respectively, bringing significant amounts of woody biomass on the market. On this point it is important to clarify that the magnitude of the recent rise in salvage loggings is varying largely between countries, with Central Europe showing a large pulse of bark beetle infestations. For example, in Czechia in 2018, salvage loggings accounted for 90% of total removals, while in Sweden it accounted for only 3%. Since 2015, Czechia has experienced the worst bark-beetle outbreak ever recorded. Therefore, total removals doubled in 2019 compared to the harvest rate in 2014 (CSO, 2019). The increase in salvage loggings might be partly responsible for increased harvesting rates observed in the EU over recent years. This illustrates that natural disturbances force significant amounts of woody biomass into the market in a very short time. The further flow of woody biomass is uncertain due to limited data availability. Damaged wood may well usually be used for lower quality wood products and for bioenergy. Further work is needed to acquire information on the woody biomass flows after salvage loggings.

3.4 Woody biomass for bioenergy in the EU[19]: a synopsis

Renewable energy in 2016 made up 17% of the gross final energy consumption of the EU. Bioenergy constituted 59.2% of all renewable sources, and more than 60% of EU domestic biomass supplied for energy purposes was wood-based (Eurostat[20], NREAP Progress Reports). As illustrated in Chapter 2, for the detailed assessment of woody biomass used for bioenergy, we rely on two main data sources: National Renewable Energy Action Plans (NREAPs) progress reports and the Joint Wood Energy Enquiry (JWEE), complemented with data from the Joint Forest Sector Questionnaire (JFSQ) for the entire EU forest-based sector.

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[19] The years assessed were prior to Brexit. 'The EU' corresponds to EU-27 + UK unless otherwise specified

[20] Eurostat nrg_ind_ren: ahttps://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_ind_ren&lang=en

Results reported here derive from the further development of Sankey diagrams of woody biomass flows (Cazzaniga et al. 2019a) and the in-depth analysis of Wood Resource Balance (WRB) sheets (Cazzaniga et al. 2019b) based of the aforementioned data sources. In this section 3.4 we present a first overview of results; a more detailed analysis will follow in section 3.5. Of all the wood used in the EU (from both primary and secondary sources, either domestically sourced or imported), 451 Mm^3, corresponding to 63%, was used for bioenergy production in 2015. Primary wood contributed to at least 37% (166 Mm^3) of the total wood used for energy. Secondary woody biomass, which comprises by-products from wood processing industry, both solid (sawdust, chips etc.) and liquid from the pulp industry (black liquor or tall oil), processed wood fuels, post-consumer recovered wood (from construction, renovation and demolition, packaging as well as old furniture), contributed to at least 49% (222 Mm^3) of the total wood for energy in 2015. Statistics also report a certain amount of woody biomass used for energy whose origin, primary or secondary, is not known. This "uncategorised" woody biomass for energy, accounts for 14% of total energy uses in 2015 (63 Mm^3). The actual origin of this biomass has implications for forest management intensity, as will be discussed in section 3.5.

The detailed composition of the woody biomass input mix used for bioenergy in the EU is shown in Figure 8.

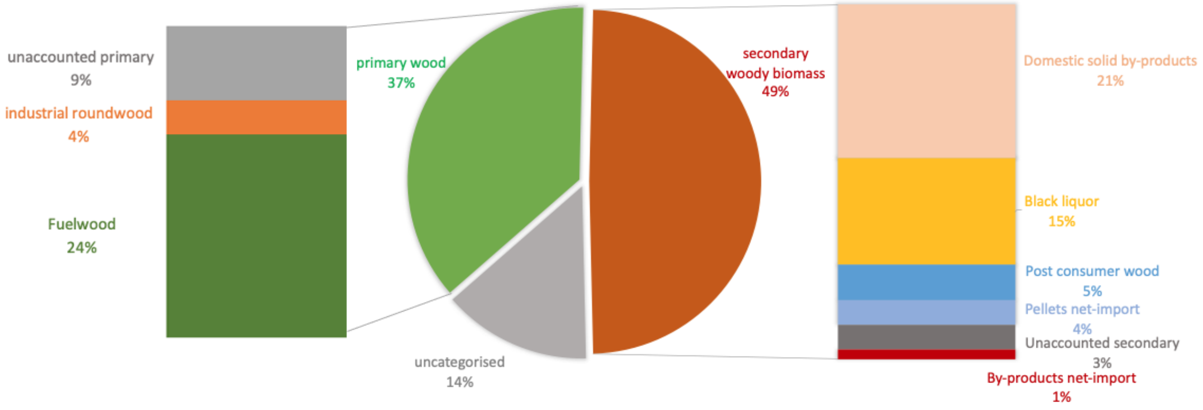

Figure 8. Origin of wood fibres used for bioenergy in the EU (2015)

According to our estimates, in 2015 primary wood used for energy was partly fuelwood (65% of primary wood), partly industrial roundwood (11% of primary wood) and partly unreported removals (24% of primary wood). Details on how these estimates were derived will be provided in section 3.5.

Fuelwood, which is composed of main stems that are normally of lower quality than roundwood used for industrial purposes, branches and other parts of tree, is wood harvested to be used directly as fuel or to produce processed wood fuels such as wood pellets and briquettes. Modelling results and previous assessments (Camia et al. 2018) indicate that approximately 40% of the fuelwood consists of main stems, with the rest being other wood components (OWC), i.e., treetops, branches, etc. In fact, following the discussion in section 3.2, out of the total annual reported removals, on average approximately 65 Mm^3 are estimated to be OWC (Figure 4), which almost entirely ends up as fuelwood. Assuming, based on IPCC default Biomass Expansion Factors (IPCC, 2003), a share of stemwood and OWC of 70% and 30% respectively in unaccounted primary wood removals for bioenergy, a broadly tentative estimate of the composition of the primary wood used for bioenergy production would be 53% (or 88 Mm^3) stemwood (industrial roundwood + stemwood component of fuelwood and unaccounted sources) and 47% (i.e., 78 Mm^3) OWC. This corresponds to 20% and 17% respectively of the total wood used for bioenergy production. Furthermore, based on knowledge and the data from the

EuroCoppice COST Action (Unrau et al. 2018), we can assume that at least half of the stemwood used as primary wood for bioenergy production in the EU is derived from coppice forests. Part of the wood used for energy is imported, although wood pellets are the only commodity significantly traded. In 2015 the net imports (i.e. imports minus exports) of wood pellets amounted to 3% of the total wood for energy mix (around 16 Mm^3). The UK accounted for 97% of EU net imports of wood pellets (JFSQ). The United States was by far the most important source of EU wood pellets imports, with a 77% share (United Nations, 2020).

Wood pellets are also domestically produced from both primary and secondary wood sources. In 2018, the total amount of wood pellets used in the EU - both imported and domestically produced - equalled some 61 Mm^3. The UK accounted for a third of this amount (FAOSTAT). After Brexit, wood pellets imports to EU-27 play a minor role (net import of 1.09 million tonnes of wood pellets to the EU-27 in 2018).

Wood pellets net-imports in Figure 8 are grouped with secondary sources. This is a needed simplification since we do not know the exact share of primary and secondary sources used to produce the imported wood pellets. However, given the relatively small contribution of wood pellets net-imports to the EU-27 bioenergy mix, we consider this approximation acceptable.

Regarding wood pellets domestically produced, data reported by MS do not allow us to quantify the share of primary and secondary wood sources. However, it is worth noting that this does not affect the assessment of primary and secondary sources shown in Figure 8, where we do not quantify explicitly the amount of domestically produced wood pellets, but rather the wood sources used to produce them.

Regarding trends, a relatively long time series is provided by the Eurostat dataset nrg_cb_rw, “Supply, transformation and consumption of renewables and wastes”, described in section 2.2.2. In this dataset, the breakdown in terms of inputs is quite coarse, hence input categories do not correspond with our detailed analysis. Furthermore, the data are provided in energy units and not in biomass amounts; albeit facilitating the comparison with other energy statistics, this further hampers the direct use of this dataset for the purpose of our report. Nevertheless, it can provide a first indication of the overall trend from 2000 until 2018. Accordingly, the total indigenous production of wood-based energy in the EU increased rapidly from 2 to 3.5 Exajoules between 2000 and 2012, i.e., by some 75% (Figure 9), and slowly in the following years. Since then, the share of other renewables has increased at a higher pace, leading to a decrease in the share of wood-based energy in the renewable energy production from 76% in 1990 to 64% in 2015.

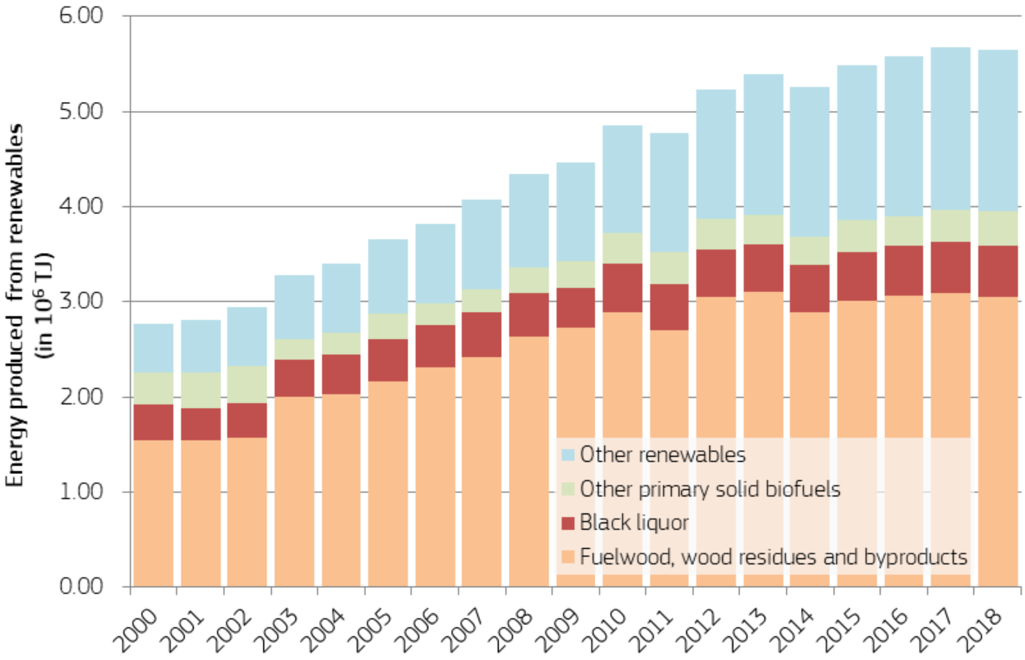

Figure 9. Indigenous production of renewable energy in the EU and share of wood-based energy (source: Eurostat nrg_cb_rw)

Looking at the growth[21] in per capita supply and consumption[22] of primary wood relative to the general economic development (GDP), it appears that removals and consumption of fuelwood (FW) has outgrown industrial roundwood (IRW) removals and consumption as well as GDP since 2007 (Figure 10). However, the growth in FW removals and consumption has seemingly slowed down since 2013 according to this data source[23]. It should be noted, though, that a detailed analysis indicates that FW removals are underestimated at the EU level. The EU is more or less self-sufficient when it comes to FW, with very limited trade. IRW removals as well as consumption has still to reach pre-crisis levels. The EU has traditionally been a net-importer of industrial roundwood. Before the financial crisis imports ranged from 20 to 26 million m^3. Since then they have never exceeded 16.5 million m^3. In 2019 even net-exports, of some 320 thousand m^3, were recorded. These were mostly spruce logs from salvage logging due to bark beetle infestations.

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[21] The graph illustrates growth rates, not absolute values. Comparisons can only be made as to growth rates. Hence, the EU was actually a net-importer (consumption larger than removals) of IRW for all the years except 2019.

[22] Apparent consumption, i.e., production + imports - exports

[23] Eurostat Table *nrg_cb_rw*: https://ec.europa.eu/eurostat/databrowser/view/nrg_cb_rw/default/table?lang=en

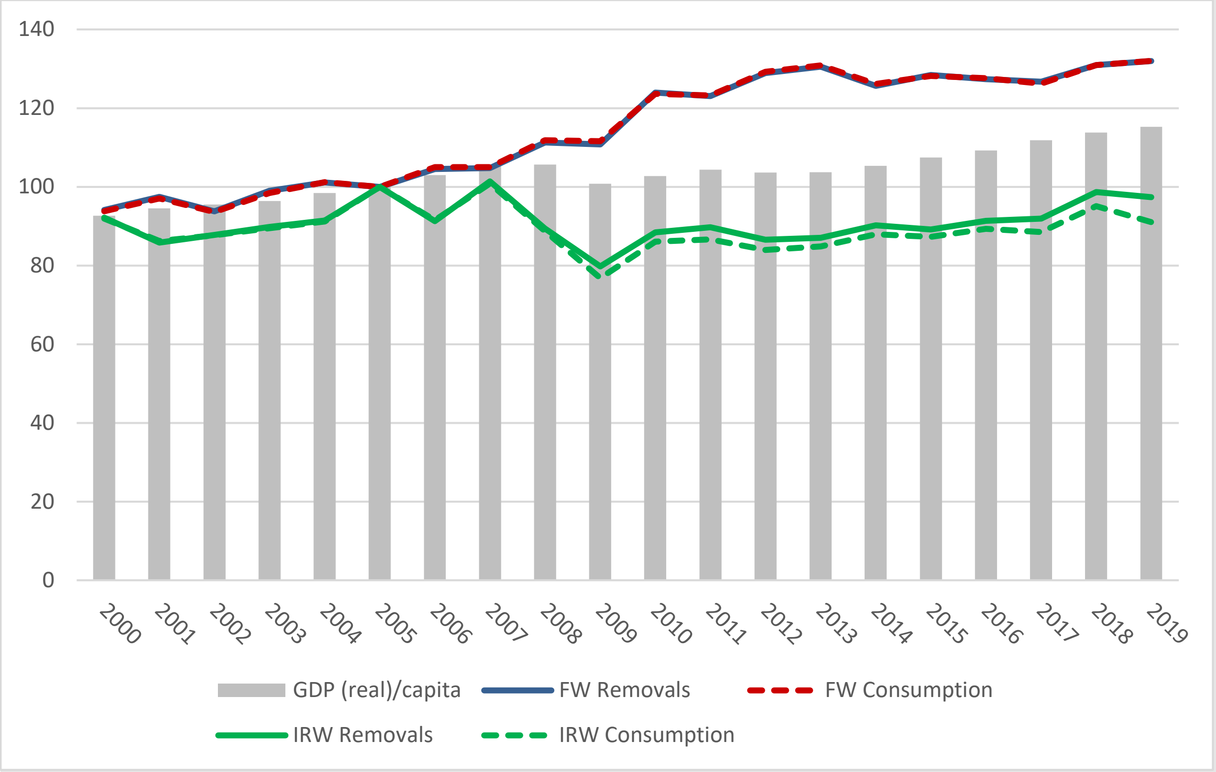

Figure 10. EU removals and consumption of industrial roundwood (IRW) and fuelwood (FW) per capita, and GDP per capita. Index 2005 = 100 (sources FAOSTAT and Eurostat (GDP and population))

The WRB time series, covering the period 2009 to 2015, is too short to be able to draw any conclusions from the trends. In addition, all markets were still very much affected by the financial crises initiated in 2008 at the beginning of this time series to be able to rely on this temporal as a benchmark. Thus, the overall trend signals emerging from the available WRB time series should be interpreted with considerable caution. Nevertheless, the details on the input mix and its changes over time provide interesting insights.

The overall use of woody biomass for energy increased by some 34% between 2009 and 2015. Although primary wood used for heat and power increased by 16% between 2009 and 2015, the share of primary wood within total wood-based bioenergy uses decreased by some 5.5% during the same period (Figure 11). The amount of uncategorised woody biomass used for energy increased by more than 52% in the studied period (with a share of the total ranging from 12% to 14% from 2009-2015). Secondary woody biomass is the largest reported source for wood-based bioenergy. The subset of secondary wood increased by 20% between 2009 and 2015. This indicates a lower growth rate compared to overall wood-based bioenergy.

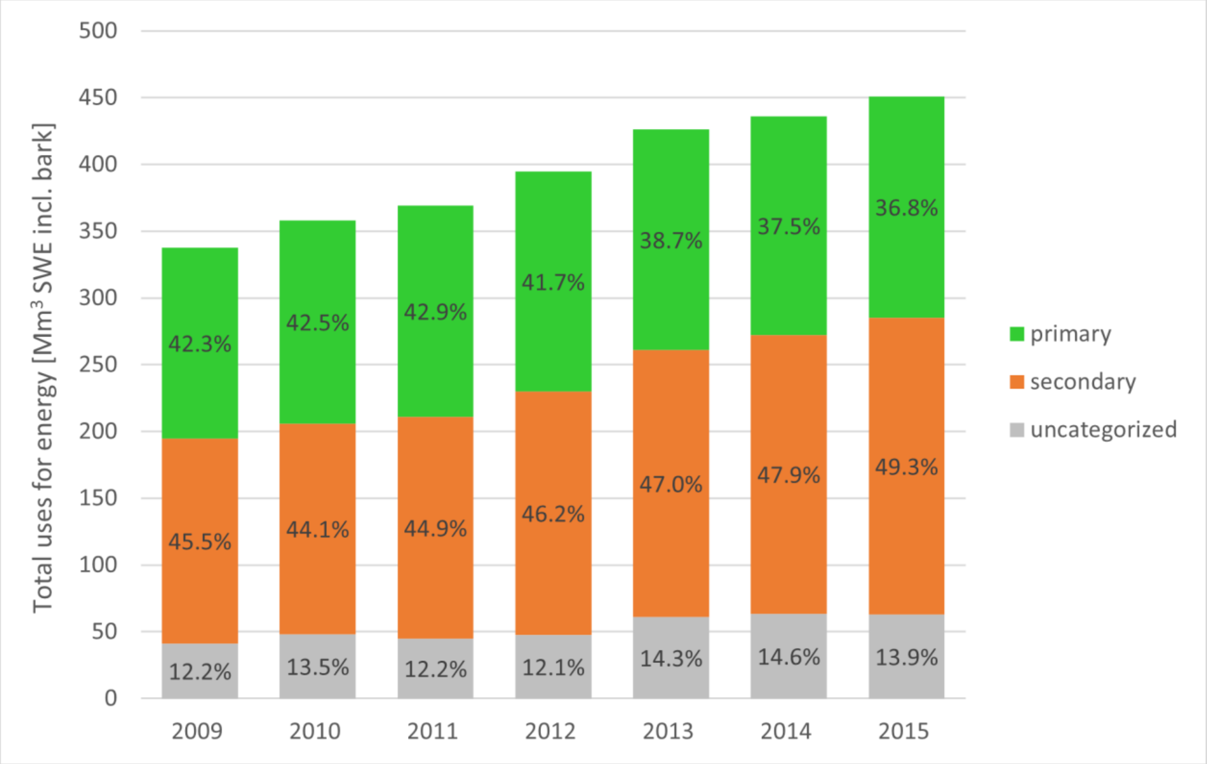

Figure 11. Total reported uses of woody biomass for energy production in the EU by category of woody biomass (million m^3 SWE incl. bark).

The availability of by-products for energy obviously depends on both (i) the amount of wood processed for material uses, which grew by merely 12.5% between 2009 and 2015, and (ii) competing demands from wood products manufacturing. The availability of other wood components such as branches, treetops etc., depends on the overall harvest volume. Post-consumer wood made up about 10% of the secondary woody biomass during the period 2009-2015, and the increase in the post-consumer wood uses for energy closely follows the trend of reported secondary woody biomass. In relative terms, the categories showing the strongest increase are wood pellets net-imports (ten times higher in 2015 compared to 2009); and industrial roundwood (three times more in 2015 than in 2009). As mentioned, UK accounted for the vast majority of wood pellets imports.

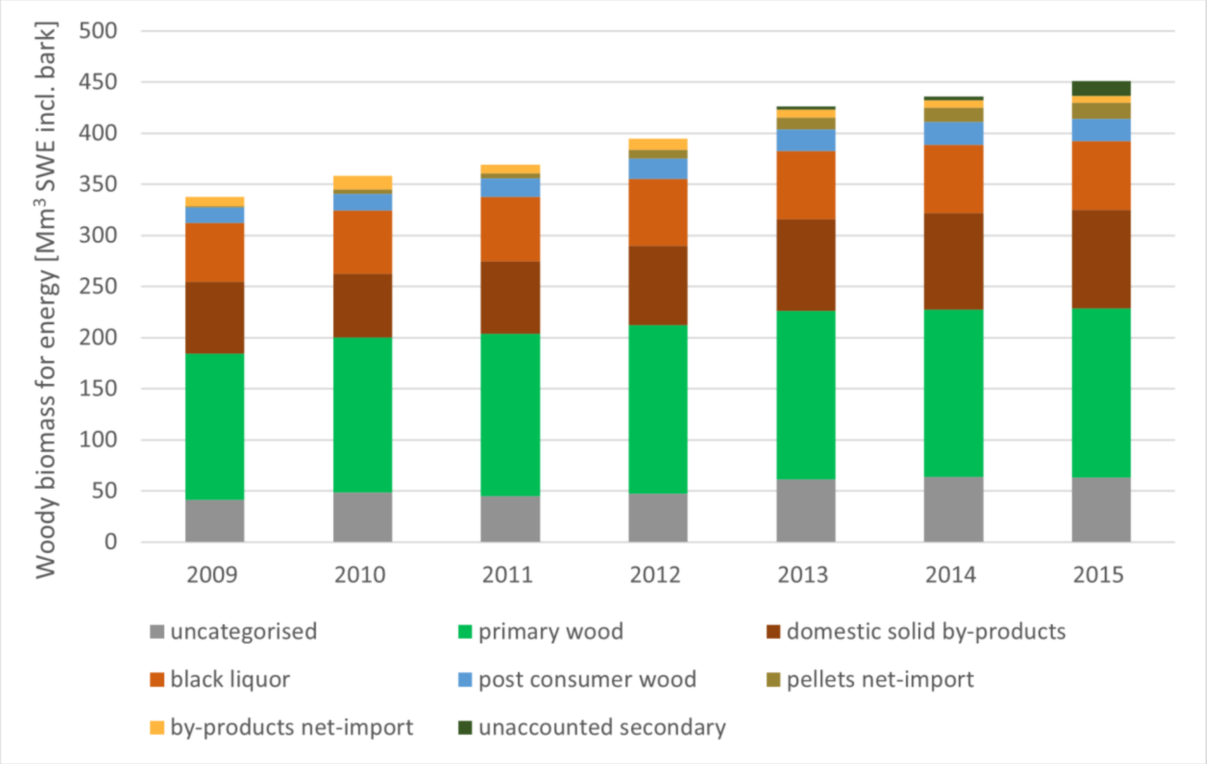

Figure 12. Woody biomass used for energy in the EU by sources (million m^3 SWE incl. bark).

3.5 Primary and secondary woody biomass for energy

The WRB is a useful tool for providing an overview of sources and uses of woody biomass, and most importantly, for highlighting data gaps and inconsistencies. As is the case for any balance sheet, the two sides (sources and uses) should balance if all data were reported completely and correctly. The left-hand side of the balance sheet presents the sources of woody-biomass: primary (from forests and from trees outside forests), and secondary (industrial by-products and post-consumer wood). The right-hand side shows in which sectors (material industries or heat and power, H&P) the woody biomass is used. All data is converted to a common measurement unit. The WRB also accounts for the fact that wood is a highly versatile material, which is used and re-used in many different processes, so-called cascading. However, it is worth noting that not all primary wood sources are interchangeable with respect to the end uses to which they may be assigned. This is also the case for secondary sources, albeit to a lesser degree. Regardless, all forms of primary and secondary wood can be burned for bioenergy. Figure 13 illustrates and summarises the pathways between the different sources and uses of woody biomass as represented in the WRB.

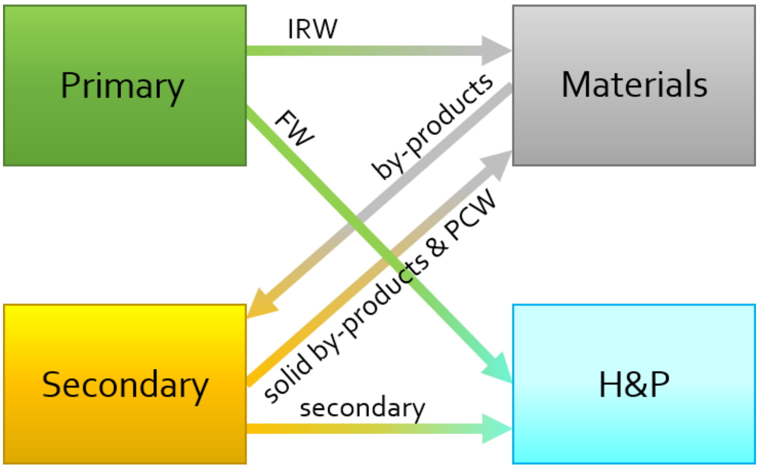

Figure 13. Flows of woody biomass among the different sectors of the WRBs.
IRW= industrial roundwood, FW= fuelwood, H&P= heat and power, PCW= post-consumer wood.

Using official data from various sources (JFSQ, Eurostat, JWEE and NREAP progress reports, as presented in Chapter 2) and building on the pioneering work by Professor Mantau (2015), JRC has developed WRB sheets covering the years from 2009 to 2015. The data have been converted to m³ solid wood equivalents (SWE) using conversion factors, and quantities of inputs and by-products have been calculated using input/output coefficients (EC-JRC, 2010). The following considerations and analyses refer to those results, summarised in Table 4. The methods used in deriving them are described in Cazzaniga et al. (2019b).

For all the analysed years (2009 to 2015), the total amount of woody biomass used in manufacturing of wood-based products and for producing H&P exceeds the total amount of reported sources (see last column “Balance” in Table 4). This gap has been growing, and in 2015 amounted to close to 120 million m³ on the overall EU level, with large differences among MS. This increase could, to some extent, reflect more complete reporting by the MS. A breakdown of the MS WRB is given in Cazzaniga et al. (2019b) and is summarised in table 3.1 of Camia et al (2018).

Table 4. Summary of the WRB sheets for the EU (thousands of m³ SWE o.b.). Positive net-trade means net-imports.

	Sources					**Uses**		**Balance**
years	**Primary**		**Secondary**		**Post-consumer wood**	**Material**	**Energy**	**Uses - Sources**
	domestic	**net-trade**	**domestic**	**net-trade**				
2009	441,936	10,784	157,445	10,281	29,766	399,650	337,568	87,007
2010	487,200	14,932	172,966	17,118	31,920	431,617	358,035	65,516
2011	494,024	12,678	180,207	13,505	33,353	440,723	369,408	76,364
2012	492,745	14,077	186,887	19,156	34,210	441,819	394,549	89,292
2013	499,778	16,459	193,496	19,075	35,618	450,360	426,128	112,061
2014	516,374	16,723	200,313	21,054	36,480	462,411	435,936	107,402
2015	522,855	17,829	203,746	21,899	36,714	469,744	451,082	117,782

Analysis of data from the JFSQ and JWEE indicates a growing share of the bioenergy production in total uses (Table 4). However, total uses include also reuse, as some of the secondary biomass used for energy is also accounted for as input for some material industry (e.g., part of roundwood entering a sawmill ends up as by-products, subsequently accounted for as wood chips used for energy generation). For details, see Jonsson et al. (2020), where data gaps are analysed more in depth.

To illustrate the woody biomass flows within the material and energy sectors in the EU we developed a Sankey diagram for 2015 (Figure 14) based on Cazzaniga et al. (2019b). Primary woody biomass used in the different sectors are mainly based on domestic removals, only a minor quantity is imported. To match declared uses, some unreported removals need to be added. The total quantity of roundwood is mainly used in the material sector, generating not only the main products, but also a significant amount of by-products. The wood-based industry uses some of these by-products, and a small amount of post-consumer wood for wood panels. By-products, represented in blue in the diagram, belong to the wider category of secondary woody biomass. A minor amount of unaccounted secondary woody biomass makes up the difference between sources and uses. It is not possible to distinguish in detail the type of secondary biomass that is unaccounted for. An insignificant amount of bark is used in the wood-based industry but it cannot be represented. Primary woody biomass used for energy may be inferior to that of secondary biomass used for energy, but it is far from negligible. Secondary woody biomass used for energy includes by-products from both domestic and imported sources, post-consumer wood, bark and some imported wood pellets. Both primary and secondary biomass used for energy are almost completely based on domestic sources. In the data sources, there is also a sizeable amount of uncategorised woody biomass, requiring some additional unaccounted primary and secondary sources for energy whose share cannot be inferred by the available data. However, the diagram shows a very good internal consistency in the material sector, so the supply of by-products is known and it is unlikely that a significantly larger supply of by-products is available. So, either a strong underreporting of secondary wood import from extra-EU countries or a strong underreporting of removals is to be hypothesised. The second hypothesis is more probable, as discussed later in the section. The Sankey shows the circular nature of the wood-based economy in terms of the use of by-products as well as recycled wood. Secondary wood makes up almost half (49%) of all the reported wood for bioenergy use, while primary wood, at a minimum, makes up some 37%, the remaining 14% being wood of unknown origin (uncategorised). The estimates of unreported removals and unaccounted secondary sources shown in the Sankey diagram are further explained in the rest of this section.

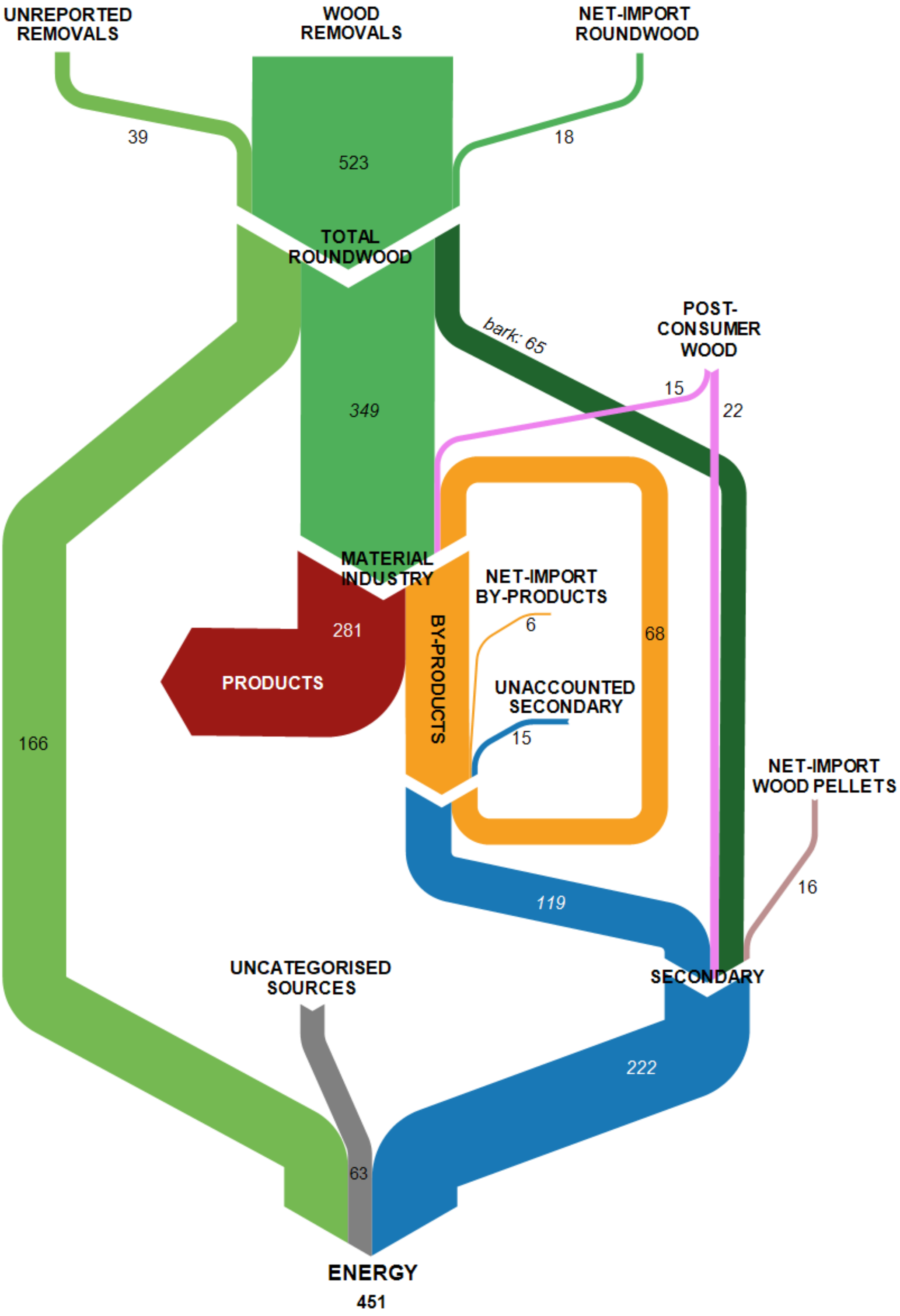

Figure 14. Sankey diagram of woody biomass flows in the EU (data 2015 in Mm^3 SWE)

Though a net exporter of several intermediate and finished wood-based products, the EU has been a net importer of industrial roundwood, forest industry by-products and wood pellets. The EU is relatively self-sufficient with regards to fuelwood, i.e. net-trade of fuelwood is rather insignificant. As for sources of secondary woody biomass, the EU production[24] has seen a continuous increase of 22 million m^3 or 143% between 2009 and 2015. Net imports of wood pellets have also seen a continuous, strong increase from 2009 to 2015: 14 million m^3, or 931%

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[24] In this chapter, the wood pellets category always includes other agglomerates (e.g., briquettes) too.

(Figure 15). As already noted, the UK accounts for the vast majority of these net imports but hardly any of the domestic production. Reported post-consumer wood has also seen a steady increase of about 7 million m^3 during this same period.

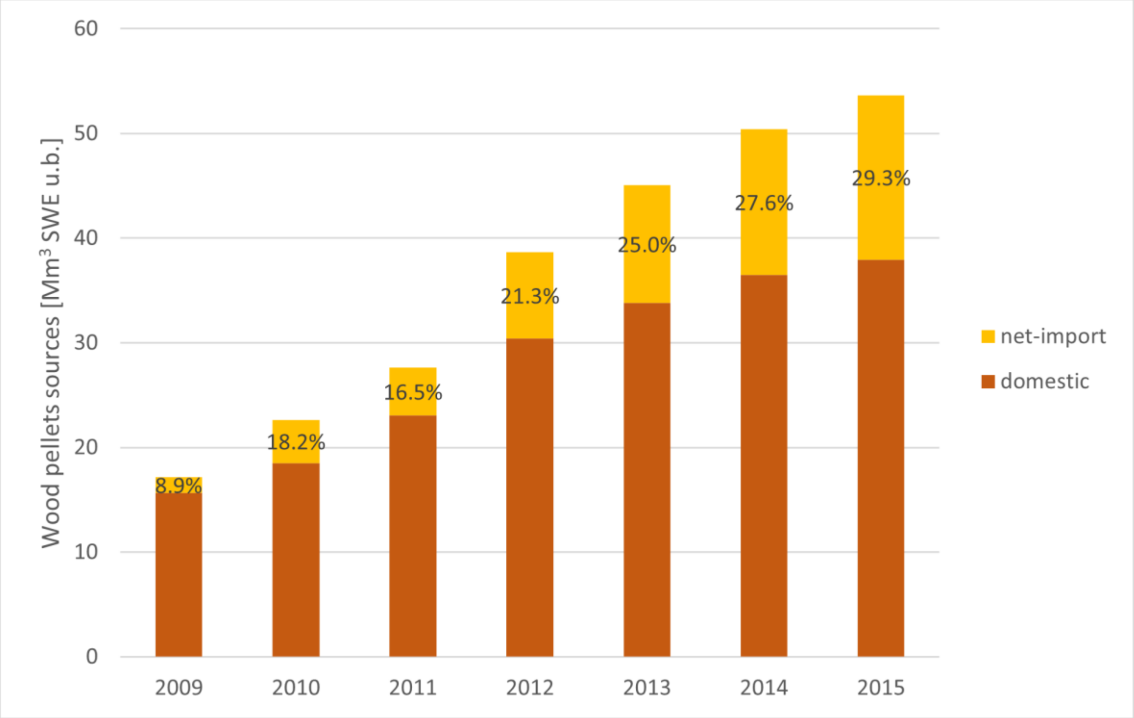

Figure 15. Reported sources of wood pellets in the EU (million m^3 SWE u.b.).

In contrast, EU net-imports of wood-based industry by-products, after some initial increase, show an overall decreasing trend from 2009 to 2015 (Figure 16). This implies that the overall increase of secondary net-trade visible in Table 4 is mainly driven by the trade in wood pellets.

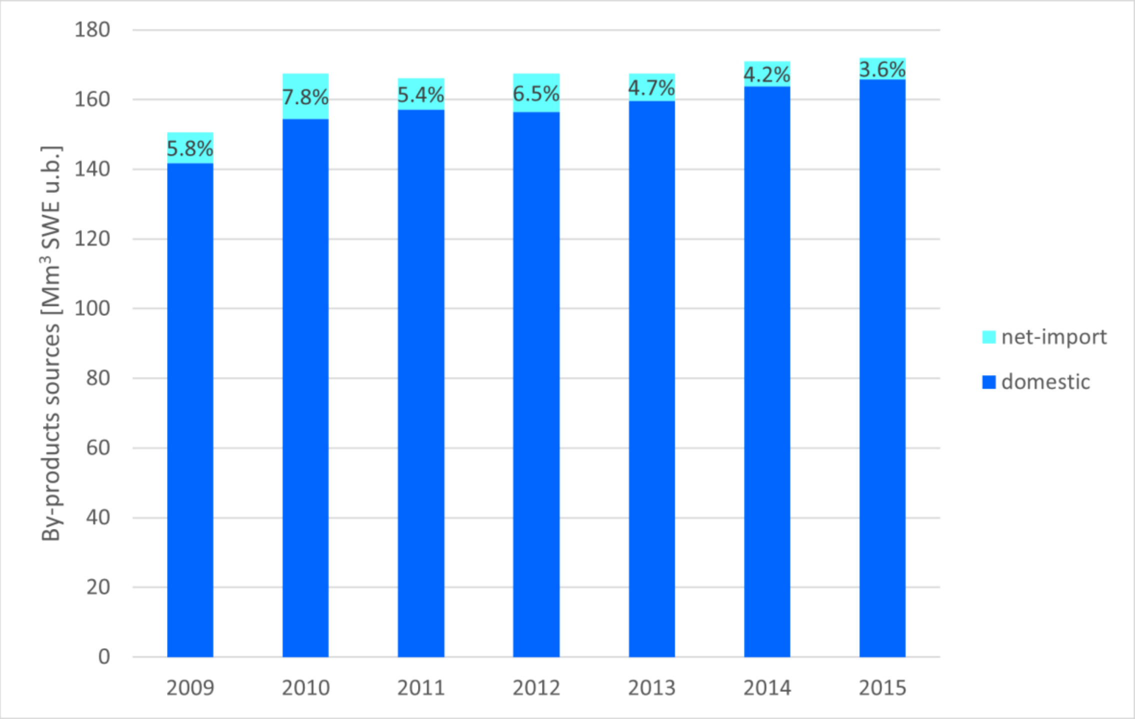

Figure 16. Industrial by-product sources in the EU (million m^3 SWE u.b.).

Solid and liquid domestic by-products result from the manufacturing of sawnwood, wood-based panels, and wood pulp. While black liquor is primarily used for energy, solid by-products are used for wood-based panels and wood pulp as well as wood chips and pellets production. Obviously, sawmilling uses only primary wood (roundwood/logs). It is possible to analyse the supply of by-products more in detail, as presented in Figure 17, where the overall input to the industries and the solid plus liquid output are represented.

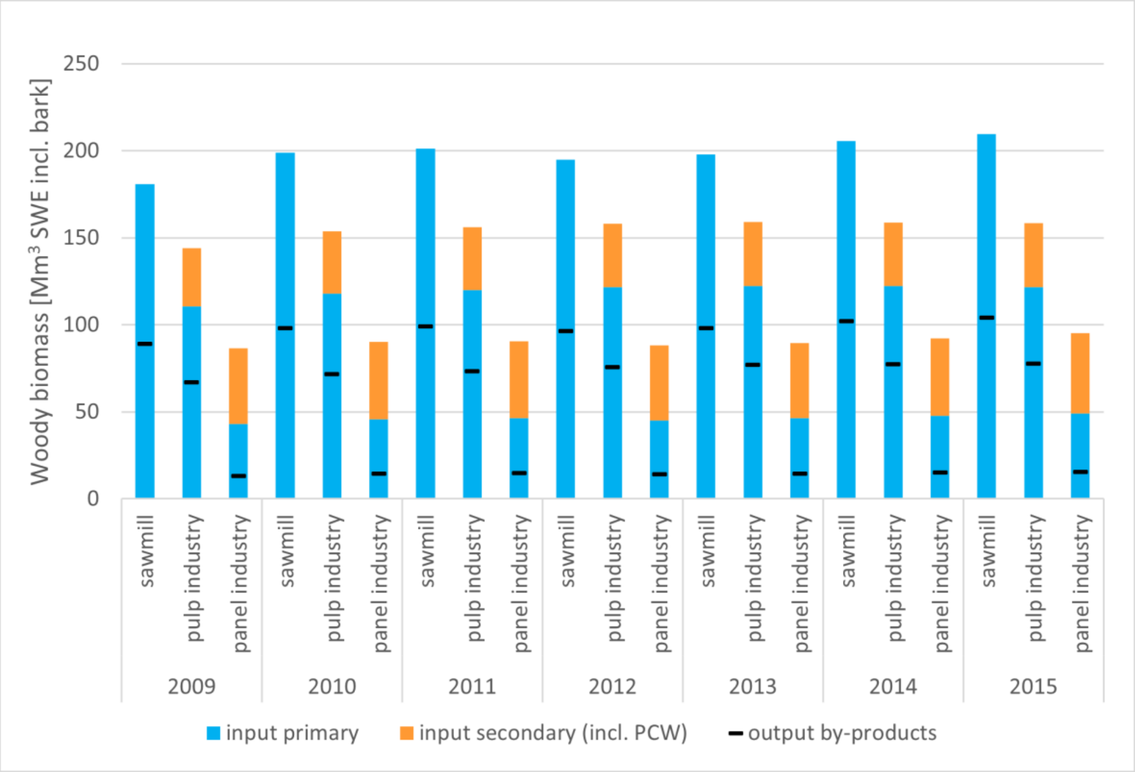

Figure 17. Input and output woody biomass for the material sector (million m^3 SWE incl. bark).

The importance of the sawnwood industry is apparent in Figure 17. Thus, sawmilling within the EU is at the same time the largest industrial user of woody biomass and the main source of secondary wood fibres, used by wood-based panel and wood pulp industries, as well as for energy (see also Cazzaniga et al. 2019a). Further, as sawlogs represent the economically most valuable part of trees, the sawmill industry is key in the mobilizing of woody biomass from forest owners (Camia et al. 2018).

Some studies indicate a strong tendency for underestimation of removals and fellings in official statistics (see, e.g., Pilli et al. 2015, Jochem et al. 2015). Hence, part of the gap between sources and uses (Table 4) can safely be allocated to primary woody biomass. We have derived roundwood indirectly, from the amount of primary wood used for material and energy (see Jonsson et al. 2020 for details), subtracting net-imports, an established procedure used by the Swedish Forest Agency, among others. For the material sector, the input of primary wood (as in Figure 17) is obtained using input coefficients. As for the energy production, the amount of primary woody biomass used is provided directly from the original data sources (converted into m^3 SWE, when given in a different measurement unit).

An important role is also played by the reported woody biomass belonging to the “Unspecified” category of the JWEE. In this case (and for some particular cases of the NREAP), it is not known if that amount of biomass concerns primary or secondary wood, or a mix of the two. The solution, detailed in Jonsson et al. (2021), is to provide a minimum and maximum value of estimated primary biomass, giving a range of expected values. In the minimum case, the uncategorised woody biomass is entirely allocated to secondary woody biomass, while in the maximum case it is completely allocated to the primary wood. The results of that exercise are reported in Figure 18. There are evident inconsistencies between JFSQ data and estimated minimum removals, where only declared uses of primary wood is included for the energy side: the difference ranges between 8.5% to 13.4%. Considering the maximum estimates, the difference is as high as 25%.

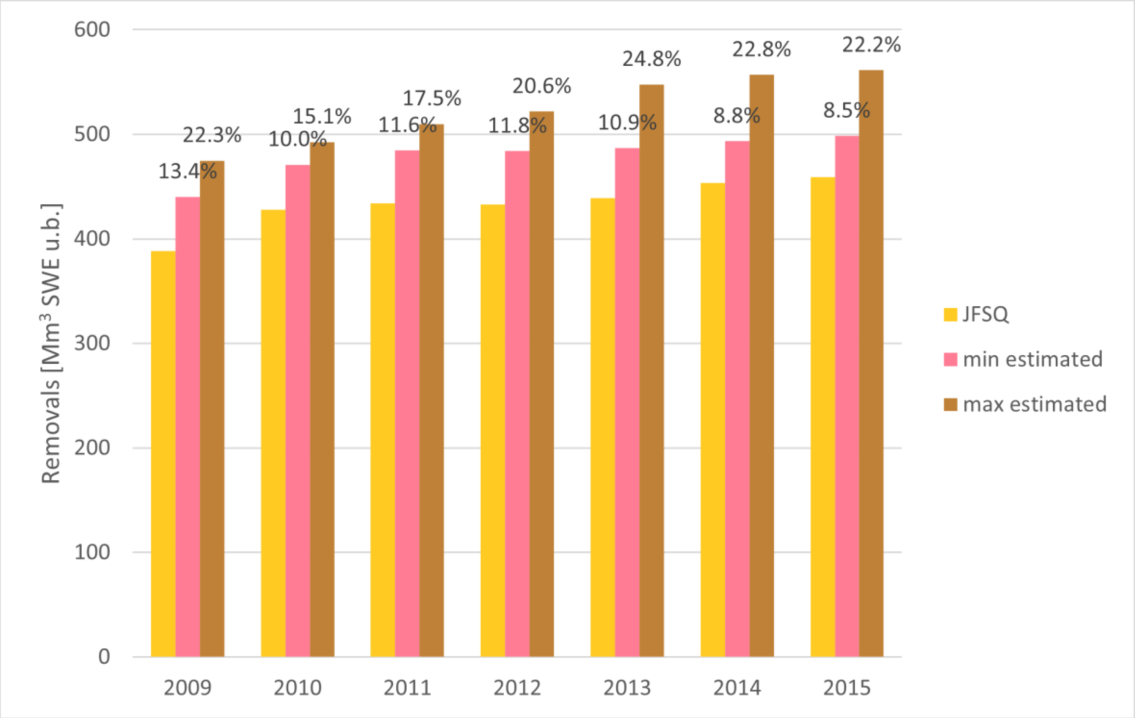

Figure 18. Total removals from forest and outside forest (million m^3 SWE u.b.), as provided by JFSQ (2017) and estimated from reported uses. The percentages depict the difference between reported and estimated removals (source: Jonsson et al. 2020).

The two different removal estimates can be converted to fellings (harvests) derived from reported uses by multiplying them by the average ratio between fellings and removals, obtained for the period 2004-2013 (see Camia et al. 2018), 1.25. Finally, they can be compared with fellings obtained by removals data of the JFSQ and with the Net Annual Increment (NAI), see Figure 19.

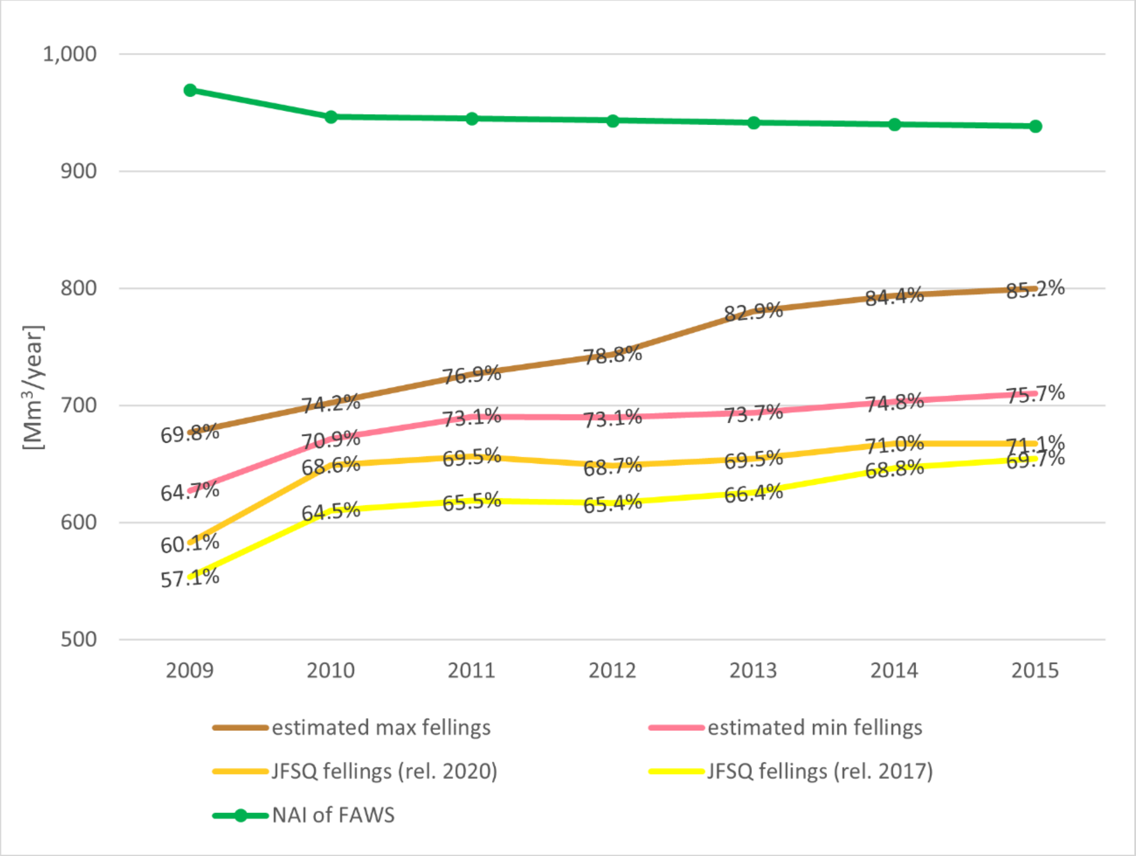

Figure 19. Comparison of net annual increment of forest available for wood supply in the EU with respect to fellings estimated from the uses of primary wood in material and energy productions and from fellings estimated from JFSQ removals. Unit: million m^3 per year. Harvest to increment ratios are reported as percentages (source: Jonsson et al. 2020).

Hence, analysis of reported uses of woody biomass signals an underestimation of removals at EU level, which translates to under-estimated fellings. This problem persists also when considering the newest 2020 release[25] of JFSQ. The most recent statistics from JFSQ for the studied years show higher removals than previous releases, however, associated fellings are still below the range of uses-based estimates. Though below the threshold of 100% of the NAI of forest available for wood supply[26] also for the maximum case, the harvest to increment ratio appears to be increasing, resulting from increasing harvest levels and a relatively stable NAI (Figure 5, Figure 19). Furthermore, judging by the increase in the difference between the minimum and maximum values over time, the estimation over time itself is subject to increasing uncertainty. The observed trend of increasing fellings to net annual increment ratio are also confirmed by the recently released State of Europe's Forest Report (Forest Europe, 2020). Absolute numbers are not directly comparable though, since here we refer to the total above ground biomass and include estimates for all EU MS.

There are striking discrepancies between declared uses and reported sources, especially for primary woody biomass. Differences between energy uses reported as being based on primary

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[25] JFSQ is subject to ex-post changes. This is further described in Chapter 2.

[26] In principle, a harvest to increment ratio of 100% signals steady state, i.e., neither growing nor decreasing growing stocks in forests available for wood (FAWS), above this level, growing stocks in FAWS diminish. NAI of the whole forest area, i.e., including forests not available for wood supply, is obviously higher, which means that there is some "untapped carbon stock" in the European forests also when the H/I ratio in FAWS reach 100%.

wood and reported fuelwood in JFSQ 2017 are substantial. Hence, the largest part of the gaps in Table 4, and consequently the biggest uncertainties of the analysis, can be attributed to the energy sector, in particular to primary wood (Figure 20).

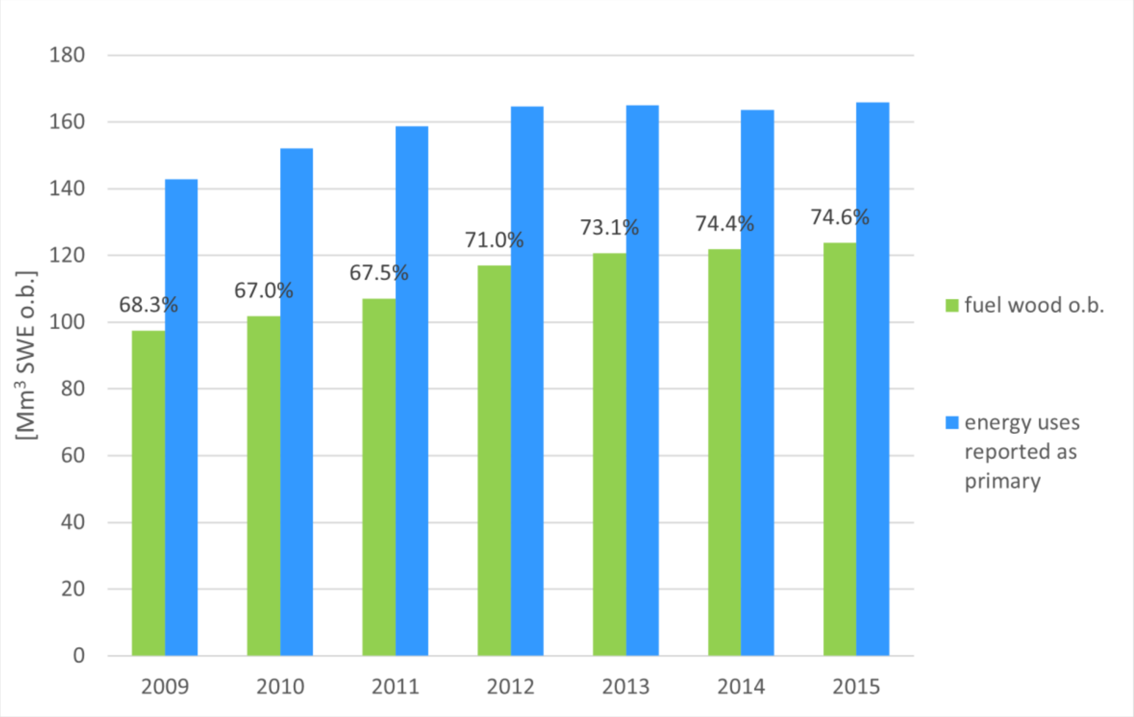

Figure 20. Reported sources of fuelwood compared to declared uses of primary wood for energy (million m^3 SWE o.b.).

It is possible to analyse the differences between the sources and uses of secondary woody biomass in a similar way as for the primary wood. Minimum uses of secondary woody biomass for energy can be estimated from the indirect wood in the lower right side of the WRB main table (Cazzaniga et al. 2019b). Maximum uses also account for the uncategorised wood for H&P.

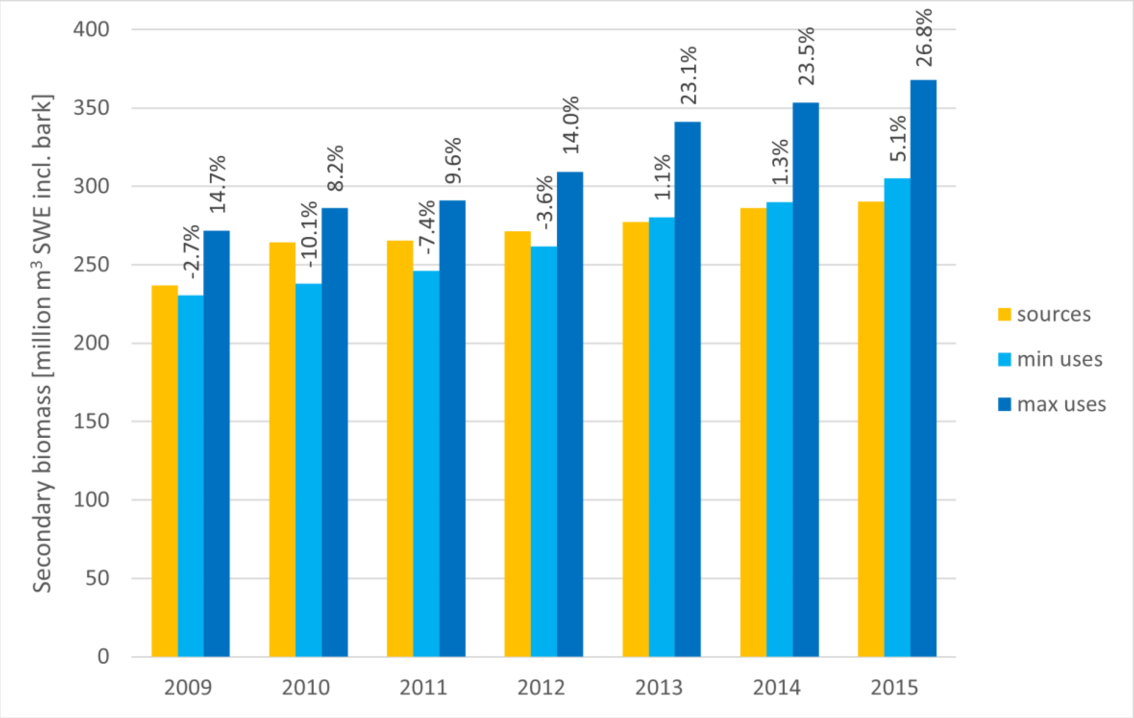

Figure 21. Sources of secondary woody biomass compared with estimates from material and energy uses in million m^3 SWE incl. bark. Percentage difference of uses with respect to the reported sources are also shown.

Figure 21 shows that the differences between sources and minimum estimated uses (that coincide with the declared uses of secondary woody biomass) are quite small. However, the differences between secondary sources[27] not used for material production and the estimated actual uses for energy (Figure 22) are much lower compared to the differences between fuelwood and energy uses of primary wood, shown in Figure 20. This further supports the finding that the largest part of the uncategorised woody biomass used for energy can be attributed to removals. The counterfactual, i.e., that uncategorised woody biomass sources are made up of secondary woody biomass, would mean that trade in secondary woody biomass is seriously under-reported. resulting in unprecedented EU net-imports, or that EU forest-based industry production is significantly under-reported (thus increasing the supply of by-products), or a combination thereof. These are all unlikely scenarios, as forest industry production and trade data are considered much more reliable than data on removals. This is the reason why, as a notable example, the Swedish Forest Agency also estimates fellings using data on declared energy use of wood, forest industry production, and trade in roundwood, wood chips and particles.

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[27] Secondary sources of woody biomass not used for material purposes, plus bark, post-consumer wood and net-imports of wood pellets, compared with indirect wood (for energy production), on the right-hand (uses) side of the WRB.

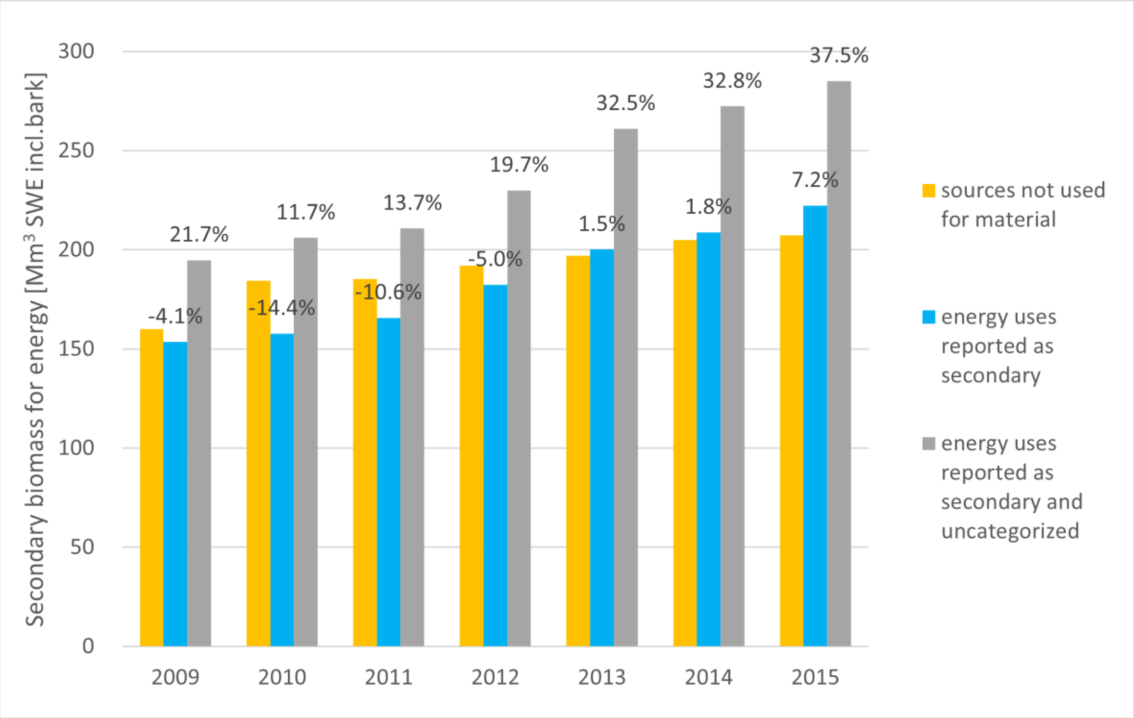

Figure 22. Secondary sources of woody biomass, in million m^3 SWE incl. bark, compared with the secondary woody biomass used for energy and the uncategorised woody biomass used for energy. Percentage difference of uses with respect to the reported sources are also shown.

Finally, from the WRBs, it is possible to evaluate the share of woody biomass used for H&P on total available sources. The total sources shown in Figure 23, include both primary and secondary sources without double counting the biomass used more than once in cascading (unlike the sources in the WRB summary of Table 4). Total energy uses in this same Figure 23 refers to the amounts of woody biomass used for energy purposes, both directly and after a further processing in material industries. They represent the woody biomass burnt by the end of the year, either as first and unique use or after a material use or a pre-processing. The comparison shows that from 2009 to 2015, the share of total (primary and secondary) woody biomass sources used for energy has grown, from 58% to 63%.

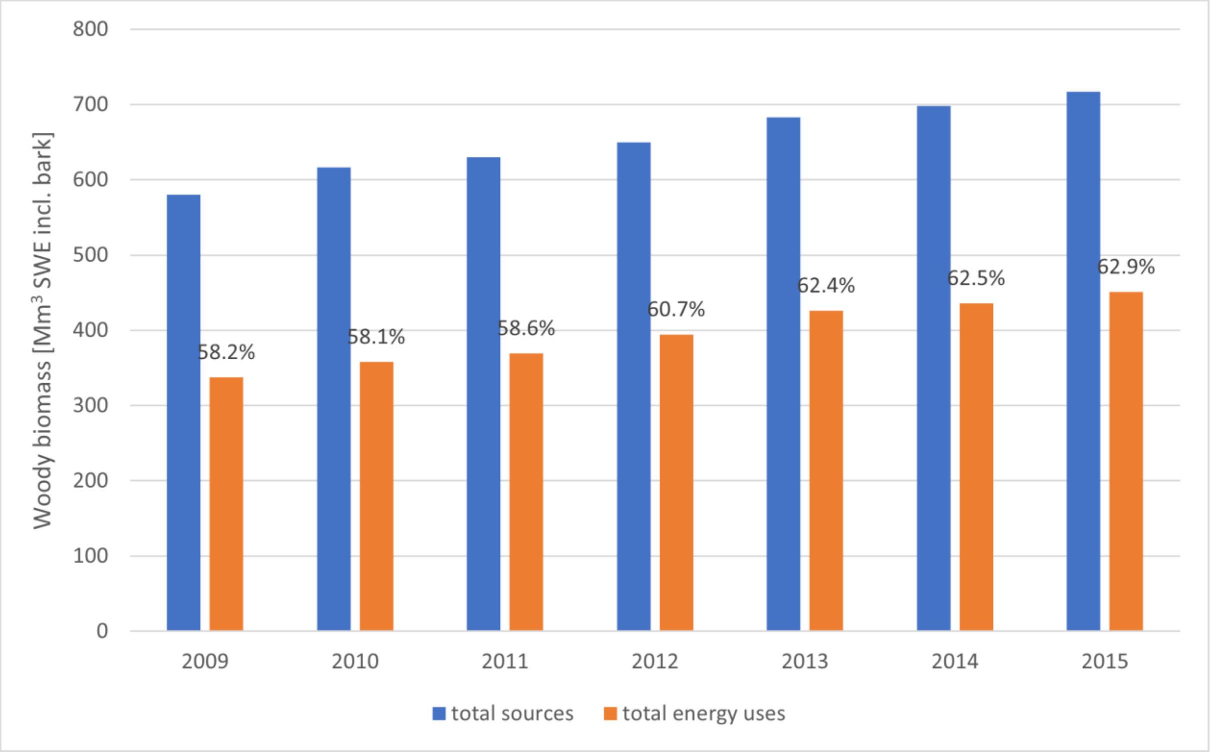

Figure 23. Total energy uses versus total sources (including unaccounted) in million m^3 SWE incl. bark. End of the year totals, no double-counting due to cascading.

3.6 Conclusions and key messages

Data indicate an increasing overall use of woody biomass in the EU, and an increase in use of woody biomass for energy use, although the growth in energy use has slowed down since 2013.

Primary wood (woody biomass extracted directly from either forests or outside forests without further treatments or conversion) makes up at least 37% of the EU wood for energy input mix. We estimated that roughly 47% of such primary wood is made of stemwood while the remaining 53% of other wood components (treetops, branches, etc.). At least half of the stemwood removed for bioenergy in the EU can be assumed to derive directly from coppice forests. Secondary wood (by-products from wood processing industry, bark and post-consumer recovered wood) makes about 49% of the EU wood for energy input mix. The remaining 14% of the input mix is uncategorised in the reported statistics, and thus cannot be directly attributed to neither primary nor secondary sources. However, our analysis clearly indicates that the category of uncategorised wood used for energy is more likely made up of primary than secondary wood.

Synergies as well as competition within the wood-based economy are evident. Similar to the energy sector, the wood-based panel and pulp industries are likewise largely based on forest industry by-products. Therefore, the energy sector, wood-based panel, and pulp industries are all dependant on the demand for sawnwood, and they compete for the same feedstocks. These interlinkages call for a holistic approach because an assessment of sources and uses of woody biomass for energy also needs to consider the whole forest-based industry.

Natural disturbances followed by salvage loggings have dramatically increased in (mainly) Central Europe since 2014, bringing significant amounts of damaged wood on the market. The oversupply of damaged wood might distort the market in the short term, by reducing wood prices and switching woody biomass flows to the energy sector.

The WRB sheets reveal considerable inconsistencies in reported data. Hence, for all the years analysed, on the overall EU level, the amount of woody biomass used in the manufacturing of wood-based products and for heat and power exceeds the total amount of reported sources. This gap has been growing over time. Our analysis suggests that the gap between reported uses and sources of woody biomass can largely be attributed to the energy sector, and mainly consists in underestimated removals. Not the least the growing tendency of reporting wood of unknown origin in energy uses is a matter of concern that can only be resolved with an improvement of data availability and quality. The new Regulation on the Governance of the Energy Union and Climate Action will hopefully contribute to achieve this. Another possible contribution to the improvement of the wood for energy statistics may derive from the implementation of the sustainability criteria for forest bioenergy under the Renewable Energy Directive (REDII, Directive 2018/2001). According to Art. 29 of REDII, sustainability criteria for forest bioenergy are applied only to biomass utilized in installations producing electricity, heating and cooling or fuels with a total rated thermal input equal to or exceeding 20 MW (Member States may apply the sustainability criteria to installations with lower total rated thermal input). Since the application of the sustainability criteria forces more stringent data reporting obligations, should the binding threshold of 20 MW be lowered, a relative improvement of the data quality and completeness might potentially be expected, due to the increase in the number of installations requested to apply the criteria.

Key messages:

- Reported uses of woody biomass for material and bioenergy have increased in the past two decades.
- The reported bioenergy use of woody biomass increased from 2000 to 2013, the growth slowed down thereafter.
- The EU has been a net-importer of industrial roundwood, by-products, and wood pellets. The UK accounted for the vast majority (97%) of wood pellets imports.
- There are inconsistencies in the available data: reported uses are consistently larger than the reported sources (117 Mm^3 in 2015), with large differences between MS.
- The gap between reported uses and sources of woody biomass can be largely attributed to the energy sector.
- Analysis of reported sources and uses of wood indicates significant underestimations in official removals data (which could be as high as up to 18%).
- Synergies as well as competition between industrial and energy uses of wood are apparent. Synergies include the bioenergy use of forest industry by-products, which enhances the profitability of the production of the main products; while competition is present mainly for sawnwood by-products. The energy sector is the largest user of EU internal wood processing by-products.
- Industrial by-products and recovered wood can be expected to only partially satisfy an increased demand from the energy sector, given that these sources are also used in wood products manufacturing.
- Accurately assessing the sustainability of woody biomass uses calls for improved availability and quality of data, which may be facilitated by a full implementation of the Regulation on the Governance of the Energy Union and Climate Action.
- Lowering the threshold of 20 MW for installations to mandatorily apply sustainability criteria for forest bioenergy might contribute to improve data quality and completeness.

- Natural disturbances followed by salvage loggings have increased dramatically in Central Europe since 2014.
- Wood oversupply from salvage logging might distort the market in the short term, reducing wood prices and switching woody biomass flows for energy.
- Further work is needed to acquire information on woody biomass flows after salvage loggings.

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4 Quantifying forest biomass in Europe

The standing forest biomass is a source of direct wood for bioenergy and material. An up-to-date, harmonised and spatially-explicit estimate of the aboveground biomass availability in European forests is critical to better understand its current and future availability. In this perspective, this chapter provides an overview of existing forest biomass data in Europe, presents the methodologies used to harmonise and compare them, describes a reference database of biomass statistics at sub-national scale and proposes an improved biomass map consistent with the forest inventory data. The content of this chapter is derived from Avitabile et al. (2020), which provides the extensive version of this study.

4.1 Background, harmonisation efforts

This chapter addresses two types of forest aboveground biomass data: biomass statistics and biomass maps. Biomass statistics are derived from National Forest Inventory (NFI) data and provide estimates of forest area, total forest biomass stock and mean forest biomass density at national and sub-national scales. Biomass maps are usually derived from remote sensing data calibrated with ground measurements and provide wall-to-wall estimates of biomass density at regional level.

Every European country has an NFI system often carried out at intervals varying between 5 – 10 years and from which it is possible to obtain reliable statistics on standing forest biomass resources (Vidal et al., 2016). Recently, the access to the NFI data has been facilitated as several countries provide online open access to their statistics. However, the analysis of the existing NFI data showed that European countries employ different forest and biomass definitions, the biomass data are not always recent or frequently updated and refer to different periods and spatial scales. It is therefore essential to perform steps to first harmonise the national biomass statistics and existing biomass maps to perform any meaningful pan-European assessment.

During the last years, dedicated harmonisation actions have been carried out on forest statistics, such as the COST (European Cooperation in Science and Technology) Action E43 (2010) and the Distributed, Integrated and Harmonised Forest Information for Bioeconomy Outlooks (DIABOLO) project (DIABOLO, 2015). These initiatives, funded by the European Commission, have focused on growing stock volume rather than total biomass, establishing reference definitions and bridging functions for common reporting, and providing harmonised stem volume estimates for Europe (Gschwantner et al., 2019).

Within this framework, the JRC has been collaborating with the European National Forest Inventory Network (ENFIN) since 2008, supporting targeted assessments to address the need for comparable and harmonised forest information in Europe.

The NFI statistics on biomass present some level of harmonisation in the regional and global assessment reports, such as the FAO Forest Resource Assessment (FRA) reports (FAO, 2020) or the State of Europe's Forests (SoEF) reports (Forest Europe, 2015). However, the harmonisation, typically in terms of forest definition and reporting period, is often performed with a simple adjustment based on linear extrapolation or expert knowledge, which may not lead to a full comparability of the estimates.

In the context of the collaboration with ENFIN mentioned above and to improve the assessment of harmonised forest biomass statistics over Europe, the JRC has launched in recent years two Specific Contracts (shortly referred to as SC13 and SC17). The aim of the contracts was to develop and apply a methodology for the harmonised assessment of forest biomass at European scale, in line with the objectives of ENFIN to promote NFIs, to harmonise forest information and support decision makers in a broad range of forest related policies.

In total, 26 NFI institutions worked together to identify a common biomass definition and estimator, which were then applied to the NFI data to obtain biomass estimates referring to the same biomass pool and estimation method for all participating countries (Henning et al, 2016; Korhonen et al., 2014).

The common definition includes all aboveground biomass compartments of the living trees, namely the aboveground part of the stump, the stem from stump to top, dead and living branches, and foliage. The biomass estimates referred to the areas defined as forest according to the FAO FRA reference definition (FAO, 2000), if the countries had sufficient information to apply this definition. The estimates were derived from a total of 516,394 field plots located in a forest area of 154 million ha.

The NFIs participating to SC13 and SC17 provided the harmonised biomass estimates also for individual species and species groups (broadleaves and coniferous). At this regard, this study found that the total biomass stock of the participating countries is almost equally stored between conifers (50.4%) and broadleaves (49.6%), with most biomass found in *Picea sp.* (22%) and *Pinus sylvestris* (19%), followed by *Fagus sylvatica* (11%), *Quercus robur* (7%), *Betula sp.* (7%) and *Quercus cerris* (4%). *Abies sp., Alnus sp., Carpinus sp., Fraxinus sp. and Populus sp.* contributed individually to about 2% of the biomass stock, and all other species (individually) for <2%.

The data harmonisation is a large and often underestimated effort, and it is a key aspect of this study. Compared to the values reported at national or international level (such as the FRA or SoEF reports), the biomass statistics produced within SC13 and SC17 have the advantage to refer to the same biomass pool using a common methodology. In addition, the biomass statistics are provided at sub-national scale, which for most countries corresponds to the NUTS-2 level, while the international reports provide data only at national scale.

The results of SC13 and SC17 represent a major step ahead towards a fully harmonised assessment of forest biomass resources in Europe and strengthened the collaboration of the NFI institutions among each other and with the European Commission. However, each NFI acquires ground data during different years that do not correspond across countries. Consequently, the SC13 and SC17 biomass statistics are not temporally harmonised but range from 2001 to 2013. Given that the biomass stock may change substantially in a time span of 12 years because of forest change processes (loss or gain) and natural forest growth, the biomass statistics were further harmonised to the same reference year (2000 and 2010) by the JRC using the Carbon Budget Model (CBM-CFS3).

The CBM is an inventory-based, yield-curve-driven model that simulates the stand- and landscape-level carbon dynamics of all forest carbon pools (Kurz et al., 2009). The model, developed by the Canadian Forest Service, was adapted by the JRC to the specific European conditions and applied to the European Union (EU) countries to estimate the forest carbon dynamics (Pilli et al., 2016a, b; Pilli et al., 2017). The temporal harmonisation was performed for 21 EU countries, for which the SC13-SC17 biomass statistics were available and the CBM was parametrized.

The JRC also supported a dedicated effort (through specific contracts) to harmonise the statistics related to the Forest Available for Wood Supply (FAWS). As for the biomass statistics, the FAWS data available in the national and international reporting are limited to summary statistics at national scale with limited comparability because of the different interpretation of international definitions or the use of different restrictions and related thresholds (Alberdi et al., 2016; Fischer et al., 2016).

Given these limitations, the JRC launched two service contracts (SC18 and SC19) with 22 European NFIs to assess, using a common definition and methodology, the main restrictions to wood availability and to quantify the forest area and biomass stock available for wood supply (Alberdi et al., 2017, 2019, 2020). The SC18 and SC19 provided harmonised data on FAWS for 243 sub-national administrative areas, thus with a much higher spatial detail on FAWS area, stock and related restrictions compared to the national data.

In this collaborative study (SC18 and SC19), forests were considered as FAWS when restrictions do not have a significant impact on the current or potential supply of wood. The restrictions are divided into economic, environmental and social restrictions. Economic restrictions are those affecting the economic value of wood utilisation and include accessibility, profitability, slope and soil conditions. Environmental restrictions consider the protected areas, protected habitats or species, and protective forests. Social restrictions include restrictions to protect aesthetic, historical, cultural, spiritual, or recreational values (Alberdi et al., 2020).

The SC18 and SC19 found that both the forest area and the biomass stock available for wood supply was larger than 85% for most countries involved in the study. The detailed description of the FAWS statistics and related restrictions is reported in Avitabile et al. (2020). The results are based on the same methodology and data used in the SC13 and SC17, making the statistics on total standing forest biomass and the fraction available for wood supply directly comparable. This harmonised and spatially-detailed information is key to better understand the factors limiting the wood availability at local level, to support and guide the mapping of FAWS using remote sensing data, and to assess and model the wood resources available currently and in the future.

4.2 Reference database of forest biomass in Europe

The best available statistics on forest biomass stock in Europe were compiled by the JRC in a reference dataset for the year 2010, with a spatial resolution ranging from NUTS 3 to national level. The biomass density and the spatial detail of the reference statistics are presented in Figure 24. Map of the reference biomass statistics for the year 2010, expressed as biomass density of the forest area (Unit: megagrams per hectare, equivalent to tonnes per hectare)..

As indicated above, it was not possible to perform a full harmonisation of the biomass statistics for all European countries. The statistics were harmonised for biomass pool and reference year for the 21 EU countries included in SC13-SC17 for which CBM was parametrized (AT, BE, BG, CZ, DE, DK, ES, FI, FR, HR, HU, IE, IT, LT, LV, NL, PL, PT, RO, SE, SK). For the five countries included in SC13-SC17 but not calibrated for CBM (CH, CY, IS, NO, RS), the SC13-SC17 statistics were harmonised only for the biomass pool. For the remaining European countries (AL, BA, EE, GR, LI, LU, ME, MK, SI, TR, UK), the reference statistics at national scale were taken from the SoEF 2015 report (Forest Europe, 2015).

These statistics were used to assess the accuracy of the biomass maps and to integrate them into an improved biomass map for Europe in line with the national forest reference values (Section 4.3). This reference database can be further updated to recent years using the CBM and the latest national statistics.

In order to have a complete view of the wood resources available in Europe, the harmonised FAWS data obtained from SC18 and SC19 were integrated with the FAWS statistics provided by the SoEF 2015 Report for the remaining countries into a reference database of FAWS data for Europe (Figure 25). The resulting database presents a variable level of spatial detail because the SC18-19 provide FAWS data at sub-national level while the SoEF Report provides only summary statistics at national level. The SoEF data refer to the year 2010, as this year is closer to the reference years of the NFI data used in the SC18-SC19.

Since the SoEF Report provides the FAWS area and related growing stock volume but not the biomass stock, Figure 25 reports the wood availability for all European countries in relative terms, and refers to the available biomass stock for the countries participating in the SC18-

SC19 (data at sub-national level) and to the available growing stock volume for the remaining countries (data at national level). These statistics were not used to assess the biomass maps, as the maps refer to the total standing biomass in the forest and not to the fraction that is available for wood supply.

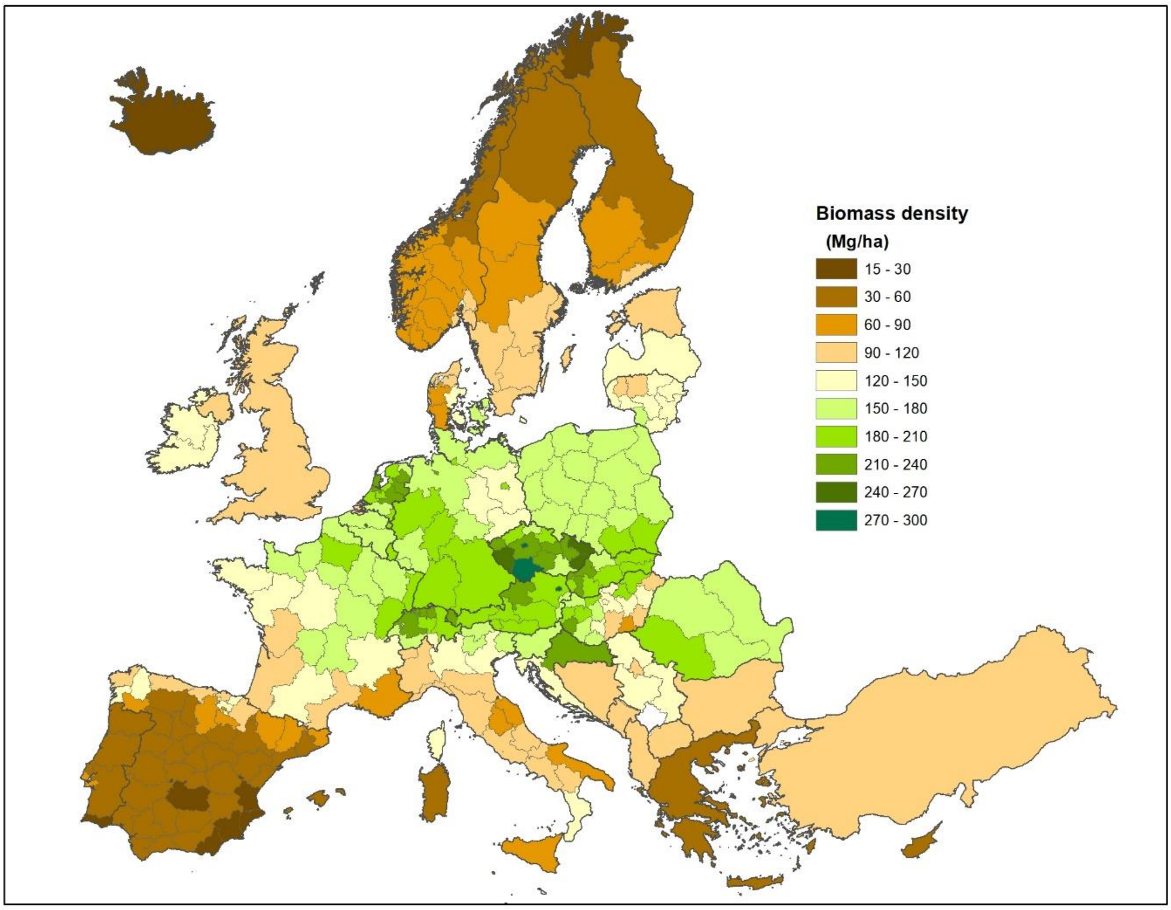

Figure 24. Map of the reference biomass statistics for the year 2010, expressed as biomass density of the forest area (Unit: megagrams per hectare, equivalent to tonnes per hectare).

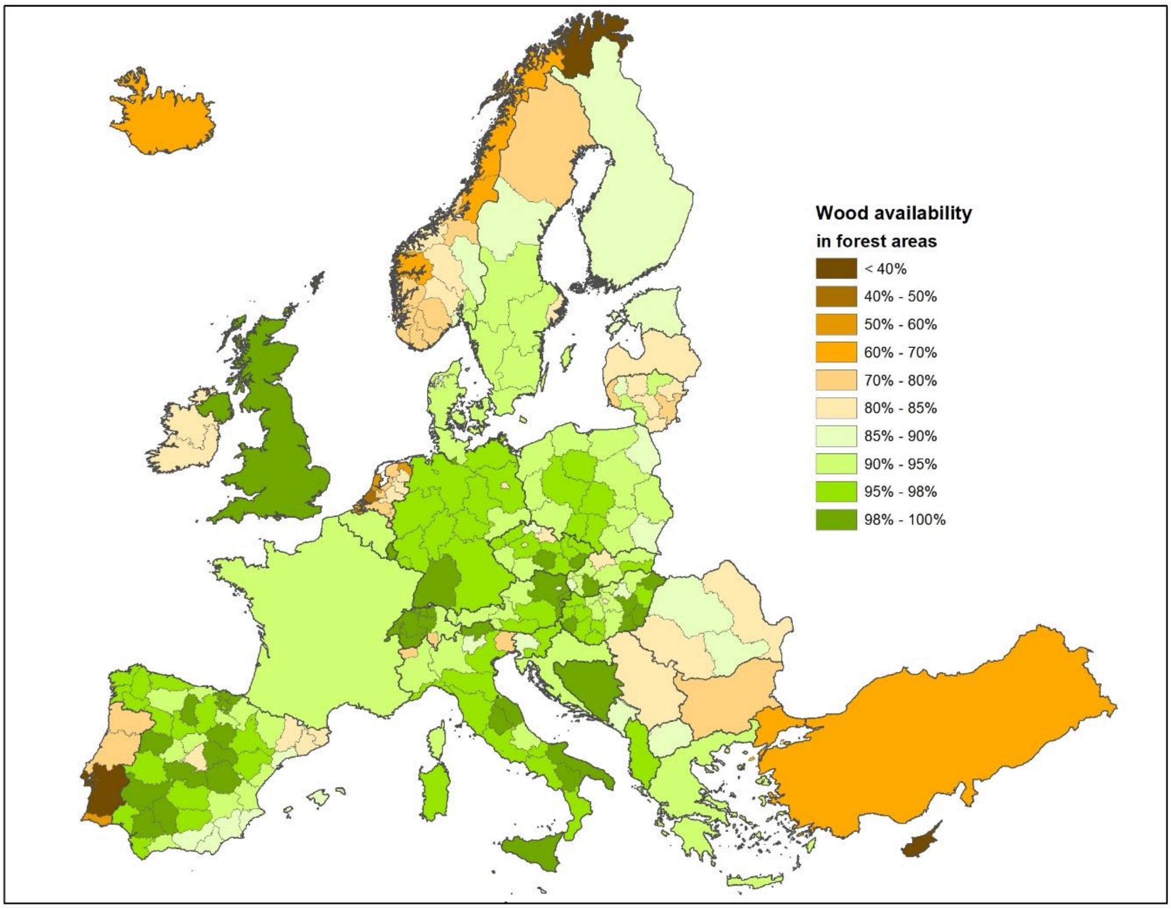

Figure 25. Percentage of wood available in European forests. The percent of wood is in unit of aboveground biomass for countries with data available at sub-national level (countries participating in the SC18-19) and in unit of growing stock volume for countries with data available at national level (data derived from the SoEF 2015 Report).

4.3 Mapping

This section describes the existing biomass maps for Europe published in the scientific literature and presents an improved biomass map that is in line with the harmonised biomass statistics. This map depicts the biomass stock of European forests at a reference year (2010) and is a basis for the estimation of the current supply of biomass resources from European forests.

Currently, there are six published maps providing forest biomass density for Europe: the datasets of Santoro et al. (2018), Baccini et al. (2017), Thurner et al. (2014), Barredo et al. (2012), Gallaun et al. (2010) and Kindermann et al. (2008). The maps present an increasing level of complexity in their modelling approaches. The Barredo and Kindermann maps essentially spatialize the total national biomass stocks using spatial data (hence, maintaining the correspondence with the total country values). Differently the Santoro, Baccini, Gallaun and Thurner maps used reference biomass data to calibrate a model based on satellite images without constraining ex-ante the estimates to match the national statistics. However, the Gallaun map was ex-post adjusted to match the regional values provided by the EFISCEN model, for the regions covered by the model.

The six biomass maps were assessed by comparing them with the harmonised reference biomass statistics for 37 European countries at national and sub-national levels (see Section 4.2) regarding the total biomass stocks and the mean biomass density. The comparison considered that the biomass maps were produced using forest maps applying different forest definitions and spatial resolutions, resulting in substantial differences in the area included, especially in the transitional areas between forest and non-forest.

The Barredo and Kindermann maps presented a total biomass stock similar to that of the reference statistics but they also covered a larger forest area, resulting in a frequent underestimation of the biomass density per unit area. The Thurner and Gallaun maps covered a similar forest area but presented a total stock lower than the reference statistics, while the Baccini and Santoro matched well the reference statistics both in terms of forest area and biomass stock.

The Santoro, Baccini, Gallaun and Thurner maps tended to underestimate at lower values and overestimate at higher values. These maps were mainly driven by models based on remote sensing data, and their uncertainty is likely due to the fact that satellite sensors have limited sensitivity to variations in canopy height and tree diameter, and no sensitivity to variations of wood density. However, thanks to the large amounts of input data and the advanced modelling approach, the Santoro map achieved higher accuracy compared to the other maps.

The biomass maps were assessed also at pixel level using the harmonised field plots produced by the SC13 and SC17. This assessment confirmed the results presented above and provided a complete validation of the biomass maps for Europe. The complete description of the map assessments using statistics and plot data is reported in Avitabile et al. (2020).

This analysis showed that in Europe the biomass maps present substantial uncertainty at sub-national and, in particular, at pixel level, where the relative error is larger than 50%. Considering that the usefulness of the maps for local management and modelling activities lie in their ability to provide accurate spatial estimates at a high and moderate resolution (i.e., at local and sub-national level), the results suggested the need for an improved product.

The error of a map can be distinguished in two components: the systematic error and the random error. Random errors are caused by unknown and unpredictable changes in the measurements or in the environmental conditions, while systematic errors result from a persistent issue and leads to predictable and consistent departures from the true value. While random errors are essentially unavoidable, systematic errors are not. For this reason, the reference statistics can be used to remove the systematic under- or over-estimation of the map estimates.

In this study, the Santoro map was corrected for systematic error at sub-national scale using the reference statistics, and it was then validated using the reference field plots. The correction of the bias of a biomass map using reference statistics requires to first match their forest area because a systematic difference between the statistics and a map may be due (in part or total) to different areas. Thus, the Santoro map was masked using an adjusted version of the Copernicus 2012 Forest Type map, which was modified to match the national statistics of forest area reported by the NFIs. The Santoro map was then corrected by removing the systematic difference with respect to the reference statistics. The bias was removed using a correction factor, computed as ratio between the reference statistics and the mean value of the biomass map over the same area represented by the reference statistics.

The result is a biomass map of Europe[28] at 100 m resolution for the year 2010 that matches the reference statistics at national and sub-national scale in terms of forest area, biomass density and biomass stock (Figure 26). This improved biomass map allows to better estimate the current and potential supply of biomass resources from European forests as well as their availability and cost, towards a better modelling and assessment of the role of forest biomass in the European bioeconomy.

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[28] The map is available in the JRC Data Catalogue (https://data.jrc.ec.europa.eu/dataset/d1fdf7aa-df33-49af-b7d5-40d226ec0da3).

The integration of the biomass map with the Copernicus 2012 Forest Type map showed that the total biomass stock is equally divided between conifers (43%) and broadleaves (43%), while mixed forests store 14% of the biomass stock. As the conifers cover a smaller forest area (38%), they present, on average, a larger biomass density (108 Mg/ha) compared to the broadleaves (89 Mg/ha), which cover 48% of the forest area. Mixed forests, present on 14% of the forest area, have an average biomass density of 97 Mg/ha.

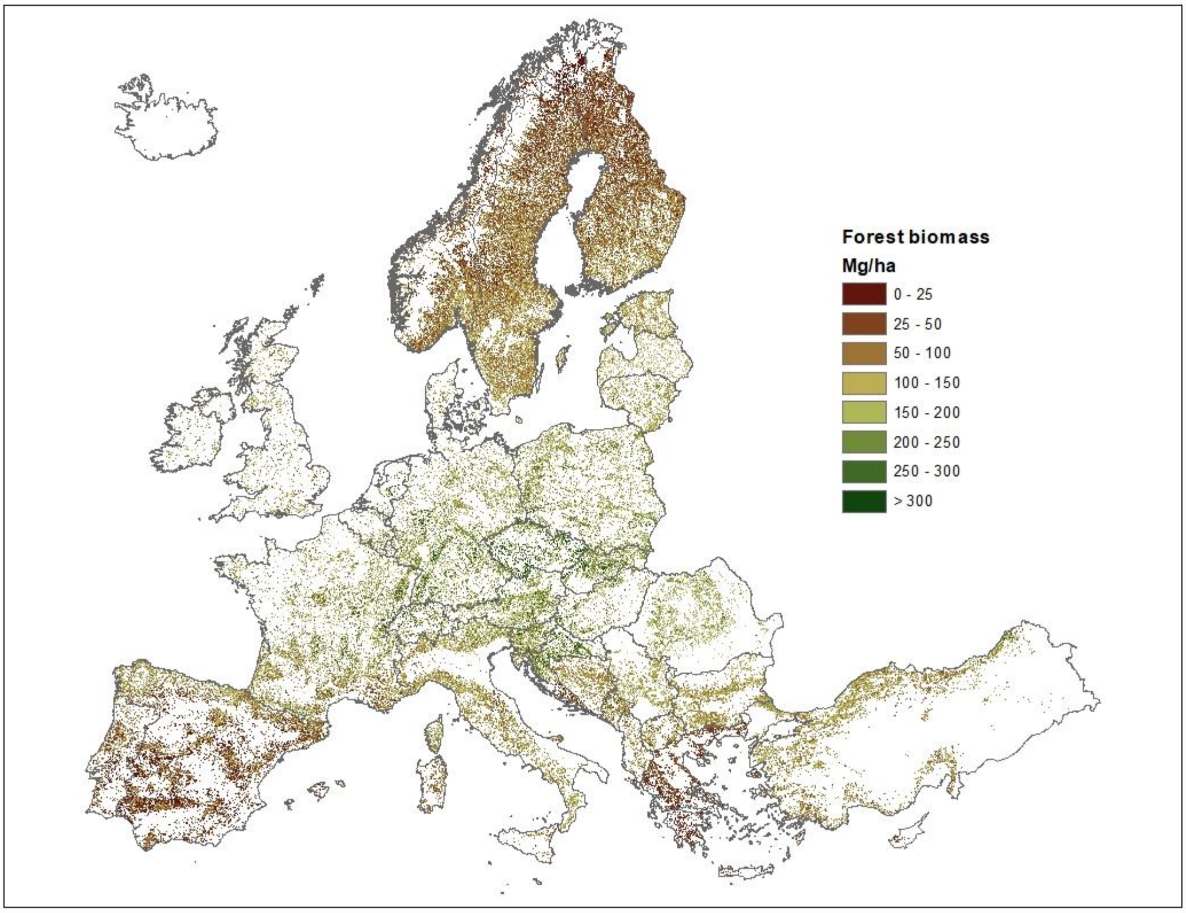

Figure 26. The bias corrected biomass map for Europe, derived from the Santoro et al. (2018) map and adjusted to match the reference statistics in terms of forest area and biomass density

4.4 The potential of remote sensing for biomass monitoring

It has been widely recognized that Earth Observation can integrate and support ground-based forest inventory data with wall-to-wall forest monitoring over large areas in a timely, consistent and independent way. Satellite and airborne data support in many ways the implementation of forest policies (e.g. related to the European Green Deal) or the analysis of potential trade-offs between economic and ecological services of European forests. In the bioenergy context, Earth Observation can provide mapping of forest biomass and other environmental properties to support the geospatial modelling of the restrictions to biomass availability, the harvesting costs, the trade-offs with other ecosystem services, and eventually lead to better assess the potential supply of biomass from the forest-based sector. They can be also useful to better measure and monitor carbon sinks in climate policies.

Earth Observation data are being increasingly used in the NFI systems, as they allow an accurate, frequent and detailed mapping of forest cover that improves the efficiency of the ground sampling (pre-stratification) and the estimation of the forest variables (post-stratification), facilitate early warnings and timely policy responses to disturbances, or provide an independent source of data to compare with sample-based statistics. However, satellite data are not commonly used for the country estimates of forest biomass because the sensors available until recently had limited sensitivity to biomass variations (Goetz et al., 2015; Avitabile and Camia, 2018). The assessment of the biomass maps presented in this Chapter confirmed that in Europe the existing maps presented moderate accuracy at local scale, which stimulated the development of a bias-corrected biomass maps that is in line with the reference statistics.

However, the field of biomass mapping from space is rapidly evolving thanks to new satellite missions and advanced modelling approaches.

The ESA Sentinel missions of the Copernicus programme currently acquire satellite data with high spatial and temporal resolutions that improve and ensure continuity to global land monitoring. Thanks to the free and open access policy of Copernicus and the interoperability with the NASA Landsat, there is an unprecedent amount of high-resolution satellite data available for forest monitoring (Zhu et al., 2019). Even though the Sentinel and Landsat sensors are not specifically designed for biomass detection, the combination of widespread data availability with big-data processing platforms makes now possible to produce temporally consistent and spatially detailed maps of forest cover, forest change and forest properties over large areas, such as the Copernicus pan-European High Resolution Forest layers, that support biomass mapping through, e.g., better stratification of forest types.

The NASA Global Ecosystem Dynamics Investigation (GEDI) mission has recently deployed on the International Space Station the first high resolution lidar sensor to acquire precise measurements of the forest vertical structure with a dense sampling scheme that is expected to improve substantially the knowledge of the spatial distribution of forest biomass at global scale.

At the time of writing, the ESA Climate Change Initiative (CCI) Biomass project is using an unprecedent multiplicity of satellite data (optical, radar and lidar) to produce global biomass maps at 1 ha resolution for three epochs in a consistent way, thus able to quantify directly biomass change to support the carbon cycle and climate modelling communities.

In addition, two satellite missions planned for launch by 2022-2023 will provide new data for biomass mapping: the ESA BIOMASS mission will bring in space for the first time a P-band radar sensor operating at longer wavelengths that directly interact with large woody elements and therefore have an enhanced sensitivity to forest biomass with no saturation effects in dense forests, and the NASA-ISRO SAR (NISAR) mission will provide data with higher spatial and temporal resolutions particularly useful for mapping low-biomass forests and their dynamics.

However, due to the orbit characteristics, the GEDI sensor is not able to acquire data on Northern Europe (above 51.6° N), while international restrictions will impede the BIOMASS satellite to operate over Europe, suggesting the need for Europe to develop an integrated forest monitoring system using the wide variety of new-generation sensors from space, air and ground.

Besides better satellites, new remote sensing technologies such as airborne and terrestrial lidar are highly promising for the acquisition of high-quality biomass reference data from local to sub-national scale (Morton et al., 2016). Compared to the spaceborne lidar, the airborne lidar has a much higher point density that provides a detailed analysis of the forest vertical structure that is highly correlated with biomass density (Asner et al., 2014) and, thanks to its good balance between accuracy, coverage and cost, it is already used by some European NFIs for the detailed monitoring of forest properties in targeted areas and to improve the national estimates. In turn, the terrestrial lidar acquires extremely dense three-dimensional measurements of the forest canopy from the ground from which tree biomass can be estimated at local scale with very high accuracy, comparable to that of destructive measurements (Disney, 2019; Calders et al., 2016). The terrestrial lidar can also be used to construct new allometric models to better estimate tree biomass using the plant parameters usually acquired in the traditional field plots (Réjou-Méchain et al., 2017).

In conclusion, as these new technologies are rapidly maturing and becoming operative, it is expected that monitoring forest biomass using remote sensing data will improve considerably in the near future. Certainly, the monitoring strategy depends on the scale of analysis (European, national, sub-national) and the forest characteristics, with substantial differences between the Mediterranean and boreal regions. Given the limitations of some satellites and the high diversity of European forests in terms of ecological conditions and dynamics, there will not be a single optimal data source for all forest types but the way towards a better monitoring will be through the skilful integration of the existing and upcoming satellite data with airborne and terrestrial lidar measurements and traditional ground plots.

For example, a cost-effective strategy may use a multi-layered approach and integrate satellite data, freely available over large areas with frequent wall-to-wall coverage, with airborne lidar flights, which are relatively costly but provide high-quality biomass estimates for mapping at sub-national scale and for satellite calibration at regional scale, and with traditional plots and terrestrial lidar, which provide accurate reference data at local scale for the proper calibration and validation of airborne and satellite data. The synergic use of these data can allow the accurate, consistent, timely estimation of the biomass stocks and their changes of European forests, and ultimately support a better assessment of the forest resources and their potential role in the bioeconomy.

4.5 Conclusions of the chapter and key messages

The overview of the existing forest biomass data in Europe described in this chapter highlights that the NFIs provide valuable reference statistics but they refer to different definitions, periods and spatial scales, with large variability especially in their temporal frequency (Vidal et al., 2016). For these reasons, their use for a pan-European assessment requires a substantial harmonisation effort, which highlights the importance of the wide collaboration with national forestry experts. Still, the harmonised statistics remain limited in their spatial and temporal resolutions and cannot always fulfil the multiplicity of applications increasingly requested from a forest monitoring system.

Earth Observation is used to integrate and support ground-based data with wall-to-wall forest monitoring over large areas with high spatial resolution in a timely, consistent and independent way. Remote sensing of forest can facilitate early warnings and timely policy responses to forest disturbances (Ceccherini et al., 2020), support the implementation of forest policies (Grassi et al., 2017) and trade-off analysis of different ecosystem services (Verkerk et al., 2014), and improve the monitoring of forest dynamics such as in the upcoming EU Observatory on changes in the world's forest (European Commission, 2019). In the bioenergy context, Earth Observation allows a better assessment of the potential supply of forest biomass through the detailed mapping of the standing biomass stocks and the geospatial modelling of, inter alia, the forest accessibility, the restrictions to biomass availability, or the harvesting costs (Mubareka et al., 2018).

For these reasons, Earth Observation data are being increasingly used in the European NFI systems in various modalities and according to the environment and forest characteristics, even though they are not yet widely used for operational estimation of forest biomass. This is mostly due because the satellite data currently available have limited sensitivity to biomass variations and cannot be easily related to ground data, which are acquired with sampling schemes not tailored to spatial data.

However, the remote sensing of forest biomass is rapidly evolving thanks to new dedicated satellite missions (Herold et al., 2019), the increasing use of airborne laser sensors for forest monitoring at sub-national scale (Zhao et al., 2018), the promising results of the terrestrial laser sensors for high-quality ground reference data (Disney et al., 2019) and a better understanding of how to collect and relate plot data with satellite data (Réjou-Méchain et al., 2019). These new technologies present enhanced sensitivity to woody biomass and are expected to substantially improve in the near future the knowledge of the spatial distribution and dynamics of forest biomass, and thus better assess the forest resources currently available and their potential role in the bioeconomy.

This chapter presented an overview of the existing biomass statistics and maps for the European forests, the methodologies used to harmonise the statistics into a reference database, the assessment and improvement of the maps to match the reference statistics, and the latest developments in the field of remote sensing of forest.

This study highlights the importance of the wide collaboration of national forestry experts under the coordination of ENFIN (the European NFI Network) to develop and implement procedures for harmonising the national data on forest biomass stock and biomass available for wood supply, which were then collated into a reference database for all European countries using the best available data.

This study also presented an approach to combine and reconcile biomass maps based on satellite data with ground-based NFI biomass statistics, towards a stronger collaboration and integration between the remote sensing community and the forestry community that can lead to promising results in view of the new technologies and upcoming development in the field of remote sensing of forest from space, air and ground.

The availability of accurate biomass maps opens the door for multiple applications related to the geospatial integration with various forest and environmental properties and the spatial assessment of, for example, the trade-offs with other ecosystem services, the relation between biomass and forest composition, management and biodiversity, or the restrictions to biomass availability.

Key messages:

- The European NFIs provide reliable reference statistics on standing forest biomass but they follow national definitions, are not frequently updated and refer to different periods and spatial scales
- The use of NFI data on forest biomass for the pan-European assessment of biomass resources requires a substantial harmonisation effort and the joint collaboration of the NFIs
- The best available statistics on forest biomass stock and biomass available for wood supply in Europe were compiled in a reference dataset for the year 2010
- Earth Observation is used to integrate and support ground-based national data for a spatially detailed and frequent monitoring of forest resources, which is currently implemented by the NFIs in varying degrees and according to national forest characteristics
- Existing satellites have limited sensitivity to forest biomass and the biomass maps assessed for Europe capture the regional gradients but have moderate accuracy at local level
- The integration of maps and reference data was used to produce a bias-corrected biomass map of Europe for the year 2010 that matches the reference statistics at sub-national scale in terms of forest area and biomass density
- Biomass mapping from space is rapidly evolving thanks to new satellites with enhanced sensitivity to forest biomass

- Improved biomass and biomass change products that will substantially improve the knowledge of the spatial distribution and dynamics of forest biomass are expected in the next 2-3 years

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5 Sustainability of forest bioenergy

In this chapter we cover the impact of forest bioenergy on both climate change (carbon) and biodiversity. However, since the carbon impacts of forest bioenergy have been debated at length (e.g. Agostini et al., 2014; Matthews et al. 2018, Giuntoli et al., 2020b) and a comprehensive assessment has already informed the definition of the REDII (EU, 2016a), we focus here mainly on explaining how and why the relevant EU legislations (REDII and LULUCF) interact in governing the use of forest bioenergy, discussing the associated risks for the overall EU GHG emissions and removals. By contrast, given the lower attention given so far to the impact of forest bioenergy on biodiversity and the condition of ecosystems, we provide new results specifically on this aspect.

This chapter is structured in the following parts: first, we explain how the concept of 'sustainable' forest bioenergy has been addressed under the directive REDII (2018/2001) (section 5.1) and explain the limitations and the main assumptions of our analysis (5.2). Second, we clarify the linkages between REDII and the emissions and removals accounted under the land use, land-use change and forestry sector (LULUCF, regulation 2018/841) (5.3). Then, we briefly summarise the status of European forest ecosystems (5.4) and the potential changes in forest management that could take place as a result of increased forest bioenergy (5.5). Fourth, we introduce methodological aspects for the assessment of the impacts of bioenergy on climate (5.6) and biodiversity (5.7). Finally, we present in-depth results from a literature review investigating the potential impacts on biodiversity of two forest management interventions that could be exacerbated by an increasing demand for woody biomass for bioenergy (5.8).

We close the chapter by combining our assessment on biodiversity impacts with the available literature on carbon impacts, we highlight potential win-win and lose-lose pathways of forest bioenergy.

5.1 Framing the problem

5.1.1 What is 'sustainable' forest bioenergy?

Sustainability is a complex and somewhat abstract concept which spans over the three dimensions of economy, society, and environment. It is thus inevitable that a variety of definitions, criteria and indicators exist, reflecting a multitude of contexts and legitimate and equally valid perspectives and worldviews, as clearly illustrated by Strengers and Elzenga (2020).

To render the concept of sustainability operational, a normative exercise is required. For instance, Giuntoli et al. (2020a) present a conceptual framework for the monitoring of the EU bioeconomy (of which forest bioenergy constitutes a sub-system), which aims to capture a systemic and holistic view of a sustainable bioeconomy, including aspects of economic profitability, social equality, and environmental protection.

Within the EU legislative corpus, sustainable bioenergy is defined in the EU Renewable Energy Directive (Directive 2018/2001, henceforth 'REDII', EU, 2018) as bioenergy produced from feedstocks complying with specific sustainability and greenhouse gas (GHG) emissions saving criteria. Only the bioenergy fulfilling these criteria may contribute towards the climate and renewable targets of countries, and be eligible for financial support. In the previous version of the Renewable Energy Directive (EU, 2009) in force until 2020, sustainability criteria were defined only for biomass used for the production of biofuels and bioliquids. With the REDII, to be transposed by countries by June 2021, new criteria are defined also cover solid and gaseous biomass fuels used in large installations for the production of power and heating or cooling. Concerning forest biomass, the most relevant new criteria are the following ones:

1. Art. 29(3), Art. 29(4) and Art. 29(5) -> No-go areas are defined for agricultural feedstocks, in which production for bioenergy is not allowed from land that was classified, in or after 2008, as primary forest, highly biodiverse forests, areas designated for nature protection purposes (including threatened or endangered ecosystems or species), highly biodiverse grasslands (natural or semi-natural) or land with high carbon stocks, including wetlands, forested areas and peatland.
2. Art. 29(6) -> the country in which forest biomass was harvested has national or sub-national laws applicable in the area of harvest as well as monitoring and enforcement systems in place ensuring:
    1. the legality of harvesting operations;
    2. forest regeneration of harvested areas;
    3. that areas designated by international or national law or by the relevant competent authority for nature protection purposes, including in wetlands and peatlands, are protected;
    4. that harvesting is carried out considering maintenance of soil quality and biodiversity with the aim of minimising negative impacts; and
    5. that harvesting maintains or improves the long-term production capacity of the forest.
3. Art. 29(7) -> Provisions for carbon accounting linking the EU REDII with the land use, land-use change and forestry (LULUCF) sector. Specifically, the country in which the forest biomass is produced shall meet the following LULUCF criteria:
    1. the country is a Party to the Paris Agreement;
    2. it has submitted a Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), covering emissions and removals from LULUCF which ensures that either changes in carbon stock associated with biomass harvest are accounted towards the country's NDC (this is the case of EU countries, which shall follow the provisions of LULUCF regulation 2018/841), or there are national or sub-national laws in place, applicable in the area of harvest, to conserve and enhance carbon stocks and sinks, and providing evidence that reported LULUCF emissions do not exceed removals;
    3. in cases where the above criteria are not fulfilled, then management systems must be in place at forest sourcing area level to ensure that carbon stocks and sinks levels in the forest are maintained, or strengthened over the long term.
4. Art. 29(10) -> The GHG emission savings from the use of biofuels, bioliquids, and biomass shall be higher than a defined minimum threshold (henceforth “GHG criterion”).

All criteria above apply to biomass used in installations with a total rated input of 20 MW or more.

The first criterion aims to ensure the protection of biodiversity. The second criterion aims to ensure that the forest biomass is produced through management practices that are legal and do not degrade the ecosystem’s health, maintain long-term productivity, etc. The third criterion aims to ensure that the carbon impact of bioenergy is properly accounted for under the LULUCF sector (see section 5.3). Following a risk-based approach, compliance with these first three criteria can be either demonstrated through effective national or regional legislation applying to the forest biomass, or through proven management systems at the sourcing area level.

The fourth criterion - based on a simplified Life Cycle Assessment methodology- aims to compare various bioenergy pathways and promote the most efficient ones; biogenic carbon is explicitly excluded from these calculations because outside the scope of the supply chain concept used in REDII (focussed mainly on fossil energy emissions), but is already accounted through the LULUCF criterion (see sections 5.3 and 5.6). The legislation, thus, clearly focuses the definition of sustainable biomass for bioenergy on two aspects: sustainable management of ecosystems and climate change mitigation. This special focus is warranted by the fact that bioenergy is peculiar among other renewable energy sources because it sits at the nexus of two of the main environmental crises of the 21st century: the biodiversity and climate emergencies.

Bioenergy, including forest bioenergy, indeed has the potential to provide part of the solution to both emergencies when biomass is produced sustainably – i.e. without causing deforestation, degradation of habitats, or loss of biodiversity – and is used efficiently. However, at the same time, the risk to aggravate one crisis to reduce the other or to exacerbate both crises is very real (IPCC, 2019). Since forest ecosystems are largely in poor ecological conditions and under worsening stressors, in Europe (Maes et al., 2020) and worldwide (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019), it is crucial to scrutinize in details the potential threats associated with an increasing demand of bioenergy.

5.1.2 How does this report support the governance of sustainable forest bioenergy?

When dealing with the management of natural resources, the meaning of 'sustainable management' changes among different socio-economic and biophysical contexts. What is preferred or satisfactory, what is physically possible to attain, which trade-offs among sustainability dimensions are acceptable, are a matter of social values and worldviews. For instance, it is likely that in contexts where 'conservation' values are predominant, management goals of forest ecosystems might be focused more on strict protection and wildlife conservation; on the other hand in contexts where 'sustainable exploitation' values are predominant, then sustainable forest management might favour wood production and income (Nelson and Vucetich, 2012).

Considering that forest management is only a part of the forest bioenergy sustainability puzzle, we argue that the governance of bioenergy sustainability is a wicked problem (Xiang, 2013). As such, it is characterized by uncertainty over consequences, diverse and multiple engaged interests, conflicting knowledge claims, and high stakes. When it comes to wicked problems, evidence cannot be easily interpreted and more scientific investigation will not necessarily reduce uncertainties and lead to the proper, or 'best', line of action. To a large extent, there are no right or wrong answers, and the definition of 'good enough' solutions is the role of policymaking, not science. For instance, no matter the amount of scientific research, it will never be possible to settle the disputes over ethical principles and diverging worldviews mentioned above.

Nonetheless, scientists can greatly support the political process by defining the boundaries of the problem and expanding the options available for decision makers, rather than suggesting unique solutions. In a way, while policy makers have the difficult task of assembling a large puzzle with multiple possible outcomes, scientists can support the process by clearly defining the pieces of the puzzle and highlighting the potential interlinkages among them. The goal of this chapter, thus, is to expand the evidence basis available for decision makers by highlighting trade-offs between climate change mitigation and impacts on local biodiversity associated with several forest bioenergy pathways. While the danger of these trade-offs has been highlighted in the latest IPCC report on land degradation as well as in IPBES reports, this chapter aims to go into more details. We do not stop at the risks associated with land use or land cover changes, but we look more in detail at the impacts of specific changes in forest management which are often suggested as a way to increase biomass supply, but which are usually difficult to capture through large integrated models and are thus often overlooked.

We do this by taking a product-based LCA approach so that we are able to attribute the assessed impacts on carbon emissions and on ecosystem condition to a specific bioenergy pathway (see section 5.6 for details).

Additionally, since we are still far from a reliable and comprehensive methodology for the quantitative assessment of biodiversity impact (see section 5.7), we rely on a literature review and qualitative knowledge synthesis as a first step to clarify the understanding of the potential impacts of forest bioenergy pathways on biodiversity.

We assert that the synthesis presented in this chapter will support policymakers in their efforts to:

- Promote forest management practices which minimize trade-offs between climate mitigation and biodiversity conservation;
- Encourage governance tools to support win-win situations and avoid lose-lose pathways;
- Provide support in applying adaptive governance tools, such as monitoring and evaluation frameworks.

5.2 Delimitations of the analysis

As stated previously, of all the facets of forest bioenergy sustainability, we focus here only on the two issues of climate change and ecosystems' condition. This means that we explicitly exclude many other aspects that characterize the broader bioenergy sustainability assessment, such as: the role of bioenergy on electricity grid stabilization; on energy security; on socioeconomic dimensions such as rural development, income, and employment; other environmental impacts, such as air pollution (Capizzi et al., 2019); other non-GHG climate forcers, such as Near Term Climate Forcers (aerosols, ozone precursors) and biogeophysical forcers; etc. Figure 27 indicates the different levels of environmental and sustainability assessments. The aspects considered in this chapter are indicated with an arrow.

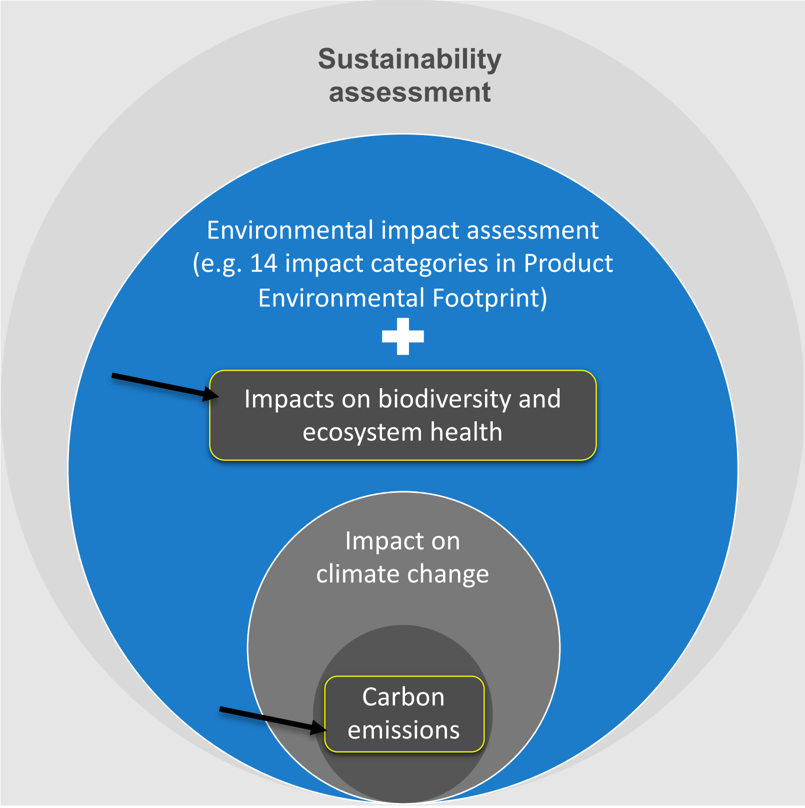

Figure 27. Representation of the comprehensiveness of various environmental and sustainability impact assessments. See also Agostini et al. (2020) for further details.

Results, especially for biodiversity impacts, are very sensitive to:

a. Biogeographic and climatic variables

b. Taxonomic groups (including differences between generalist and specialist taxa, or species of conservation interest)

c. Spatial and temporal scales considered

d. Attributes of biodiversity and aspects of ecosystem condition considered

Our assessment favours a broad-ranging synthesis over specific case studies because our goal is to highlight pathways and management options which are likely to cause negative impacts and which should thus be discouraged in the name of the precautionary principle[29], and to provide insights for further research.

For the literature review we relied on search queries (see Annex 1), but we also expanded the review based on relevant papers cited in the first list of articles. Since our main goal was to generate a high-level synthesis of knowledge and distil lessons learnt, we focused mainly on already existing reviews and meta-analysis. It is possible that the literature reviewed does not capture the totality of the available information. For instance, it appears that there is a research bias for the impact of logging residues removals (section 5.8.1) so that most of the studies refer to temperate or boreal forest ecosystems. Furthermore, there appears to be a paucity of on-site empirical studies comparing the status of plantations with natural, native forests in the US South (Petrokofsky et al., 2020), even though those play a significant role in wood pellets supply to EU for energy.

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[29] Article 191 of the Treaty on the Functioning of the European Union

5.2.1 Assumptions and delimitations

Conscious that every model and assessment result is conditional on the assumptions that lead to it (Saltelli et al., 2020; Saltelli and Funtowicz, 2014), we gather here the main and most influential assumptions driving the assessment in this chapter (Box 1).

BOX 1: Assumptions

1. This work is informed and driven by the precautionary principle. Increasing bioenergy demand is likely to drive changes in how forests are managed that could place additional pressures on ecosystems already in poor condition. It is thus imperative to have a clear understanding of the risks and benefits associated with these changes.
2. Assumptions are compatible with product-based LCA, thus this study is designed to attribute impacts to specific pathways (not an economy-wide GHG assessment).
3. The impacts of each bioenergy pathway are evaluated against a counterfactual, i.e. a reference use of the biomass or of the land (thus the results should be interpreted as conditional to the chosen reference).
4. Interventions assessed are not due exclusively to bioenergy demand but whether or not we do assume they are does not change the findings.
5. Assessment on carbon and biodiversity impacts is based solely on direct impacts and excludes indirect, market-mediated, second-order effects.
6. Authors' expert judgement are inevitably embedded in the outcome.

1. Worldviews. If the question is 'Is forest bioenergy sustainable?' the answer might be positive or negative depending on who attempts to answer it, and how. In other words, the answer is to some extent in the beholder's eyes. We argue that this question is ill-posed because the governance of bioenergy sustainability, like many other complex socio-ecological systems, is a wicked problem (Xiang, 2013). Indeed, interest groups on opposite sides of the debate claim that 'the science is clear…' in supporting their positions. When it comes to wicked problems, to a large extent there are no right or wrong answers, and the definition of 'good enough' solutions is the role of policymaking, not science. This does not diminish the role of scientists, who are expected to use the best available evidence to identify worst case scenarios and win-win pathways, and test the robustness of the bioenergy regulatory framework.

   The precautionary principle is the overarching worldview which has driven the goal and scope of the assessment. In a context where the forest ecosystems are considered to be in a poor condition in the EU (Maes et al., 2020) (although improving for a number of indicators, section 5.4) and under increasing pressure globally (IPBES global assessment, 2019[30]), possible large scale increase in forest bioenergy demand is likely to change the way forests are managed (section 5.5). This could alter the balance between the numerous ecosystem services that forests are expected to deliver. It is thus crucial to have a clear understanding of the risks and benefits associated with these changes.

2. The main method used for the assessment is product-based LCA Sala et al. (2016), aimed to identify the impact of specific pathways (section 5.6). This approach cannot be overlapped neither with the REDII GHG criterion approach (Directive 2018/2001, Art 29(10)), nor with the GHG accounting under LULUCF. While the REDII methodology has the scope to benchmark different pathways on a common scale - its aim is mainly focused on supply-chain efficiency - it does not include any accounting of biogenic-C cycle, nor of counterfactual uses for land, nor market-mediated impacts, and it is thus

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[30] https://ipbes.net/global-assessment

not designed to represent the actual climate impact of bioenergy pathways. On the other side of the spectrum, LULUCF GHG accounting (whose forest component is described in section 5.3) has the main goal of tracking the impact of land management choices towards defined country-level climate targets. The specific pathways followed to achieve such targets may influence the cost-effectiveness of the choices made, which is important. However, this has a relatively low importance as long as its impact is appropriately accounted for and the target is achieved. Matthews et al., (2015) find that the EU GHG reduction targets could be achieved with different levels of bioenergy penetration, but when looking in detail at the contribution by each energy source to the overall GHG emissions (i.e. through the product-based LCA used here), they found that forest bioenergy could have a positive or negative GHG impact, depending on the type of feedstock considered and, more importantly, on the forest management practices assumed to take place in the future.

In synthesis: as long as the GHG accounting is robust (i.e. no management-driven emissions remain unaccounted) and the overall country GHG target is met, any policy decision at country level concerning the management of natural resources in the energy mix can in principle be considered acceptable. This may include the choice to use forest bioenergy even when not helping to reach the climate targets, and the choice not to rely on bioenergy at all even if certain bioenergy pathways could help reach the targets.

3. The impacts of each bioenergy pathway in sections 5.8 and 5.9 are evaluated against a counterfactual, i.e. a reference use of the biomass or of the land. The results of the assessment, thus, should be interpreted as conditional to the reference chosen (Agostini et al., 2020). Detailed counterfactuals used are reported in sections 5.8 and 5.9. Because of the differences in scope between the LCA approach used here and the LULUCF regulation (described above), the counterfactuals used here are not necessarily those used when accounting for the GHG impact of forest bioenergy under LULUCF (i.e. the Forest Reference Levels).
4. The interventions assessed (increased removal of logging residues; afforestation; conversion of natural forests to plantations) might be driven by bioenergy demand, but also by other drivers. While we have not assessed these economic linkages explicitly, it is worth noting that there is abundant literature available presenting, and invoking, these interventions as clear opportunities to produce additional biomass for bioenergy (Giuntoli et al., 2020b). Further, even if the intervention is only partially linked to bioenergy demand (directly or indirectly), it is worth to assess its impacts that will then be proportionally allocated to bioenergy.
5. Similarly to the point above, it is worth noticing that the assessment on carbon and biodiversity impacts is based on direct impacts only and excludes indirect, market-mediated, second-order effects. These might mitigate or worsen the direct impacts assessed here, but would require a broader modelling framework. We suggest potential future research to tackle these impacts in section 5.9.2.
6. The qualitative assessment in this chapter is based on the literature reviewed, but it still inevitably reflects our own expert judgement and the assumptions illustrated above; different authors could come to slightly different conclusions reviewing the same exact literature. However, while quantitative methods for biodiversity impact assessment are being developed (section 5.7), we believe the synthesis of knowledge in this chapter is a good starting point to facilitate the comparison among pathways, highlighting risks and red flags and contributing to an incremental understanding of the impacts of bioenergy on carbon emissions and ecosystems' condition (EU, 2016a)

5.3 Clarifying the link between REDII and LULUCF and its implications.

5.3.1 How the carbon impact of forest bioenergy is accounted in the EU

This section clarifies the rationale and mechanisms behind the EU climate and energy policies that govern the use of forest bioenergy and the accounting of the associated carbon impacts, namely REDII (directive 2018/2001) and LULUCF (regulation 2018/841). The concepts illustrated in this section are further elaborated in a scientific paper (Grassi et al., in preparation).

Figure 28 summarises the links among the different tools within the EU legal corpus that define the governance of the climate and environmental sustainability of forest bioenergy used in the EU. Specifically, as described in section 5.1.1, within the REDII, Article 29 lists several sustainability criteria that forest biomass used for bioenergy must comply with in order to be eligible to count towards each country's renewable energy target.

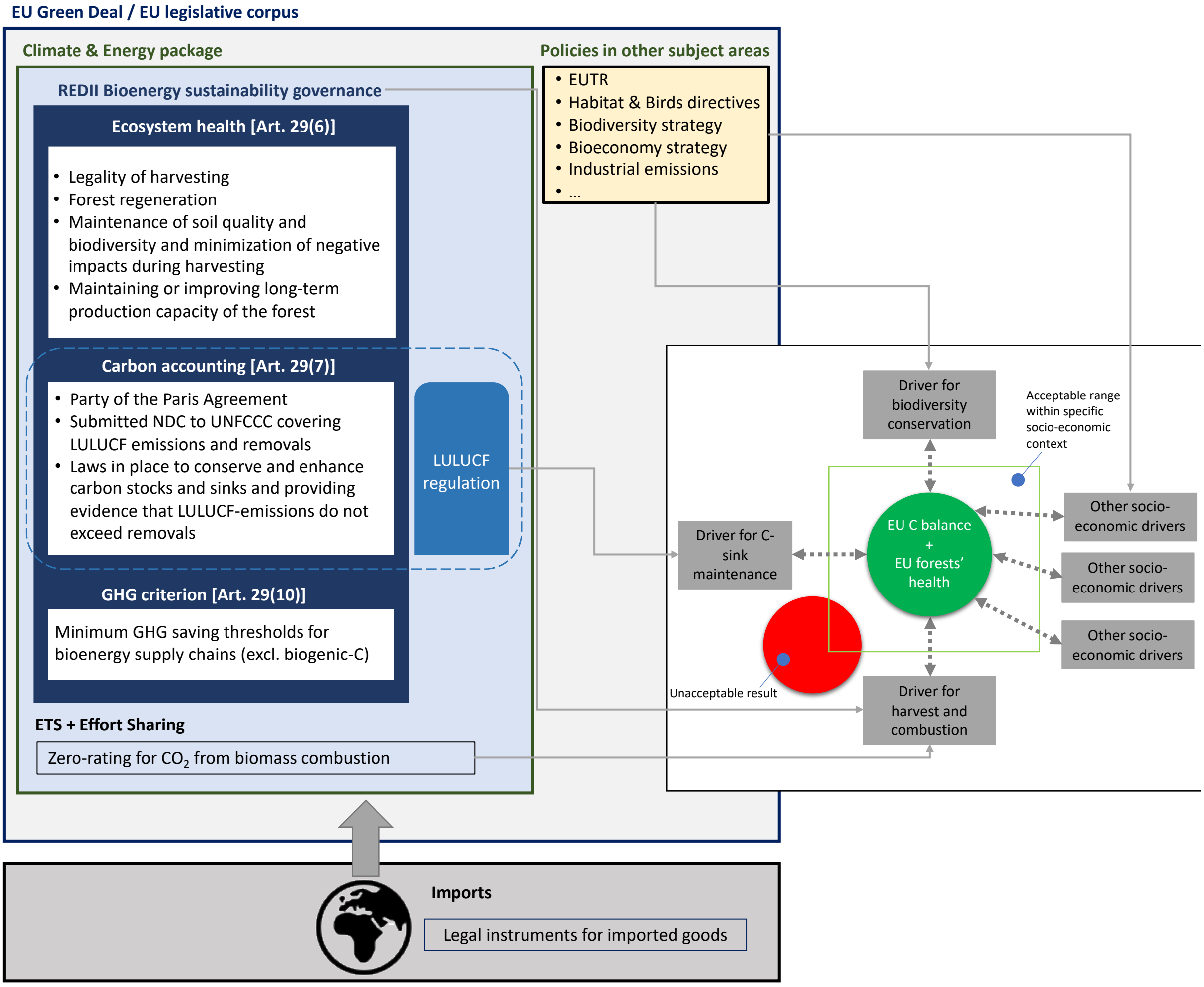

Figure 28. Schematic representation of the tools and interactions among them, for the governance of climate impacts and environmental sustainability of forest bioenergy in EU (from Grassi et al. in prep.).

These criteria were the result of a long political process, informed by a comprehensive assessment of the status of scientific understanding of forest bioenergy carbon accounting (EU, 2016a). Despite the ongoing wide-ranging and sometimes bitter debate, both in the US (see e.g. Booth, 2018; Cornwall, 2017; Dale et al., 2017; Sterman et al., 2018a and in the EU (see e.g. Agostini et al., 2017; Beddington et al., 2018; Brack, 2017; Cowie et al., 2017; Norton et al., 2019; Searchinger et al., 2018) on the role of bioenergy within climate change mitigation strategies, many of the arguments raised from both sides of the bioenergy debate have indeed already been considered by the European policy makers. For instance, an option to include biogenic-C accounting within the GHG criterion (art. 29(10)) was discarded (EU, 2016a pag. 36) also because of the crucial importance of value-choices involved in defining the calculation methodology (i.e., subjectivity in the choice of counterfactuals)[31]. A similar debate took place concerning the governance of risks of Indirect Land Use Change (ILUC) for biofuels: Palmer (2012) highlighted how the focus of the political discussion narrowed down to a highly technical discourse around modelling parameters and assumptions, which inflamed the debate and impeded the progress towards broader, reflexive, risk governance tools. In time, indeed the political choice superseded the technical debate by not embracing model results, but rather by acting on the main driver of the impact, i.e. on demand of food and feed-based biofuels (Directive 2015/1513). While the role of scientists was essential to bring the problem of ILUC to the light (Searchinger et al., 2008), the artificial taming of a wicked problem did not aid the policy process, but rather it caused a long and bitter debate which created large economic and political uncertainty. The REDII process benefited from the ILUC experience; the legislators chose not to focus on direct accounting of all biogenic-C flows, but rather leveraging other legal tools within the Climate & Energy package, such as the LULUCF regulation, and including corresponding criteria in the revised Renewable Energy Directive.

Indeed, within the heated scientific debate on forest bioenergy, a central argument is that emissions from biomass burning are not counted (zero-rating) at the point of combustion by the users of this biomass. For the EU27+UK, these emissions are considerable (around 330-380 $MtCO_2$ for the year 2015, see Fig. 29 in Box 2) and are indeed not counted in the energy sector. However, those who criticize the EU for the “the simplistic assumptions of carbon neutrality and treating biomass as renewable” (e.g. Norton et al., 2019) apparently overlook the importance of LULUCF regulation.

If the EU ETS and REDII assume zero rating of emissions at the point of biomass combustion, it is because these emissions are already counted in the LULUCF sector, as a change in carbon stocks. This approach is adopted by the IPCC guidelines for national GHG inventories (IPCC 2006, 2019) and by the UNFCCC for the accounting under the Paris Agreement. The rationale for this approach includes mainly practicability and the need to avoid double counting.

There are actually concrete reasons why emissions from biomass burning are not counted in the energy sector. In fact (see Grassi et al., in preparation), counting emissions in the energy sector when the biomass is actually burnt while avoiding double counting with LULUCF would be extremely difficult. The difficulty is because, as illustrated in chapter 3, the biomass burnt for energy purposes comes from very different and complex pathways: some is a primary wood from biomass harvested few months before (e.g. branches), some is secondary wood arising from the processing of wood harvested possibly few years before, some is waste wood from biomass harvested possibly decades before. Since the emissions and removals reported and accounted in LULUCF are based on the annual change in carbon stock (or the annual biomass gains minus losses), accounting forest bioenergy under the energy sector would imply a retrospective (and unrealistic) attribution of what is burnt to the biomass harvested in specific past years, and an ex-post subtraction of this harvested amount from the LULUCF accounting, to avoid double counting.

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[31] We can illustrate the complexity and subjectivity of the exercise by considering the definition of a counterfactual for harvest residues. This would have required the normative definition by the Regulator of, at least, the following parameters: a) What are the existing fate of the biomass if not used for energy? (e.g. slash-burning or decay in the forest?); b) The decay rate for residues left in the forest (i.e. depending on climatic area, wood type, wood size, wood position etc…); c) The time horizon at which to evaluate the analysis (e.g. what is an ‘acceptable’ payback time for bioenergy compared to fossil sources?). All of these choices would heavily influence the final carbon balance for bioenergy produced from logging residues. See section 5.6 for further technical details.

In addition, accounting biomass in the energy sector would disincentivise the energy use of wood residues (because the burning of biomass emits more CO_2 per unit of energy than fossil fuels), despite leaving these residues in the forest means that they will gradually decompose, releasing their carbon to the atmosphere. This consideration should not be read as suggesting that all residues should necessarily be burnt, because they play an important role in preserving the biodiversity and fertility of the forest.

BOX 2: Emissions associated with forest bioenergy in the EU (from Grassi et al. in prep.).

Figure 29 compares the CO_2 emissions calculated from the woody biomass used for bioenergy in the EU (estimated in chapter 3) with the total biomass used as fuel reported in the EU GHG inventory 2020. Since reported emissions include also those from agricultural biomass and waste burning, to derive emissions from woody biomass alone we assumed the share of woody biomass in the EU primary production of bioenergy reported in the EU energy statistics (Eurostat[a]). The two estimates of emissions from woody biomass burning are approximately aligned (red line and blue dashed line in Figure 29), and apparently confirm the slightly overestimated increasing trend 2009-2015 of the reported biomass used for bioenergy as discussed in chapter 3. Overall, in 2015, EU emissions from woody biomass burning ranged from 350 to 380 $MtCO_2$. By applying a displacement factor of 1.32 tCO_2-equivalent / oven-dry tonnes (based on LCA data and Matthews et al. 2015; see also Supplementary Information of Grassi et al. 2019), it can be estimated that in 2015 the equivalent fossil-based GHG emissions, avoided by the use of bioenergy, would have been in the range of 250-270 $MtCO_2$.

This comparison of biomass vs. fossil-based emissions is informative, but alone cannot not be used to draw conclusions on the negative or positive climate impact of forest bioenergy. On the one hand wood-based bioenergy indeed emits more GHG when combusted, per unit of energy, than the equivalent fossil-based energy substituted. On the other hand, it should be considered the actual composition of the woody biomass input mix and its trend before drawing conclusions.

Following what illustrated in section 3.4, for the year 2015 about 20% of this biomass can be broadly estimated as stemwood from primary wood (of which at least half is likely from coppice forests), while a larger part would come from either primary other wood components (tree tops, branches, that would have anyway emitted CO_2 in their decaying processes if left in the forest as residues, about 17%) or from secondary sources (by-products of wood processing industries, bark, post-consumer wood, about 49%); the remaining 14%, being reported as uncategorized, cannot be attributed (see Figure 8).

Based on this analysis, it could be preliminary concluded that the large majority of forest bioenergy currently used in the EU is based on residues and the widely recommended “cascade” approach (EU 2015). However, the increase in woody biomass used for energy production from 2005 to 2018 (about 34%, dashed blue line) seems mainly associated to an increase in fuelwood (see Figure 10). More importantly, the large uncertainty in the bioenergy input mix highlighted in chapter 3 prevents to assign a high confidence to the conclusion above.

Overall, a greater certainty on the composition of the bioenergy mix is a prerequisite for increasing the confidence on the positive climate impact of the current wood-based bioenergy used in the EU.

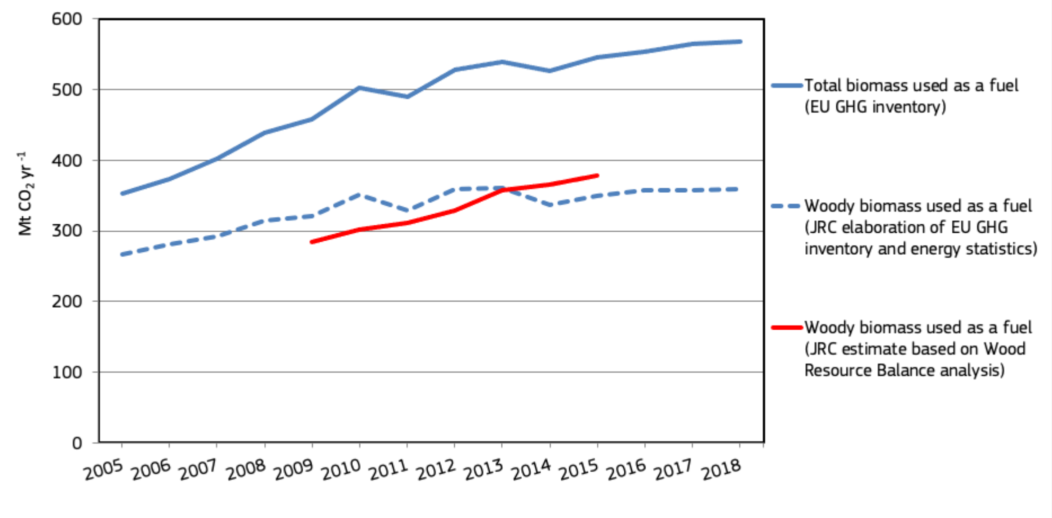

Figure 29. CO_2 emissions of biomass used as fuel in the EU27+UK[b]

[a] https://ec.europa.eu/eurostat/web/energy/data/database

[b] For information, the share of UK emissions from total biomass burning (solid blue line) relative to the EU27+UK was 3% in 2005 and 8% in 2018.

To fully appreciate the implications of this approach, that forest bioenergy is counted in LULUCF and not in the energy sector, it is important to understand *how* LULUCF counts forest bioenergy within the EU 2030 climate and energy framework (Figure 30), and *why.*

Assessing the climate change mitigation outcomes in the forest-based sector is far more difficult than in other GHG sectors (e.g. energy, agriculture). This is because forest-related fluxes are affected by simultaneous natural and anthropogenic processes that are complex and difficult to disentangle, and by age-class legacy effects that are determined by past forest management and natural disturbances (Grassi et al., 2018). In the context of country mitigation targets (e.g. Kyoto Protocol, Paris Agreement), this complexity has been addressed through policy-negotiated "accounting rules", aimed at better quantifying the results of mitigation actions, and therefore quantifying the forests' contribution toward the target. The accounting rules are important because they deeply influence the credibility of forest-related mitigation. Learning from previous experiences, aas discussed for example by LULUCF IA (EU, 2016b), Grassi et al. (2018), Korosuo et al., 2020, and after a long policy process, the EU decided to measure the impact of forest mitigation actions during 2021-2030 through the "Forest Reference Level" (FRL) concept (Regulation 2018/841). The FRL is a country-determined projected level of forest emissions and removals against which future emissions and removals will be compared. This comparison will generate accounting "credits" or "debits" (e.g. when the sink is greater or smaller than the FRL, respectively, see graph in Figure 30) that will count toward the country's climate target[32]. While credits are capped, therefore potentially limiting the incentive to increase the sink, any debit would need to be compensated by extra emission reductions in other sectors.

Unlike the 2nd commitment period of the Kyoto Protocol, where these FRL projections (called Forest Management Reference Level, FMRL) could include policy assumptions, with the risk of inflating the real impact of mitigation actions (see Grassi et al., 2018), the FRL approach adopted in Regulation 2018/841 is exclusively based on the continuation of forest management practice and wood use (i.e. the ratio between energy and material use of wood) as documented in a historical reference period (2000-2009), taking into account the age-related forest dynamics but excluding policy assumptions. As a result, the impact of any change in management or wood-use during the compliance period (2021-2030) will be reflected in the climate accounts, like in other GHG sectors. The only difference with other sectors is the impact of forest age dynamics, i.e. where forests are getting older, continuing the past management may involve increasing total harvest in the FRL. Therefore, the only bioenergy emissions that may remain unaccounted for are those associated with the age-structure dynamics, that is, with the increase in harvest which is exclusively due to more area of forest becoming mature after 2020 relative to the reference period. The rationale of this approach, which represented a political compromise, is not penalising countries for choices taken decades or centuries ago that had affected the age structure of their forests[33]. Beyond the impact of age-related dynamics on total harvest, any increase in the ratio between energy and material use of wood relative to 2000-2009 will be fully reflected in the LULUCF accounts.

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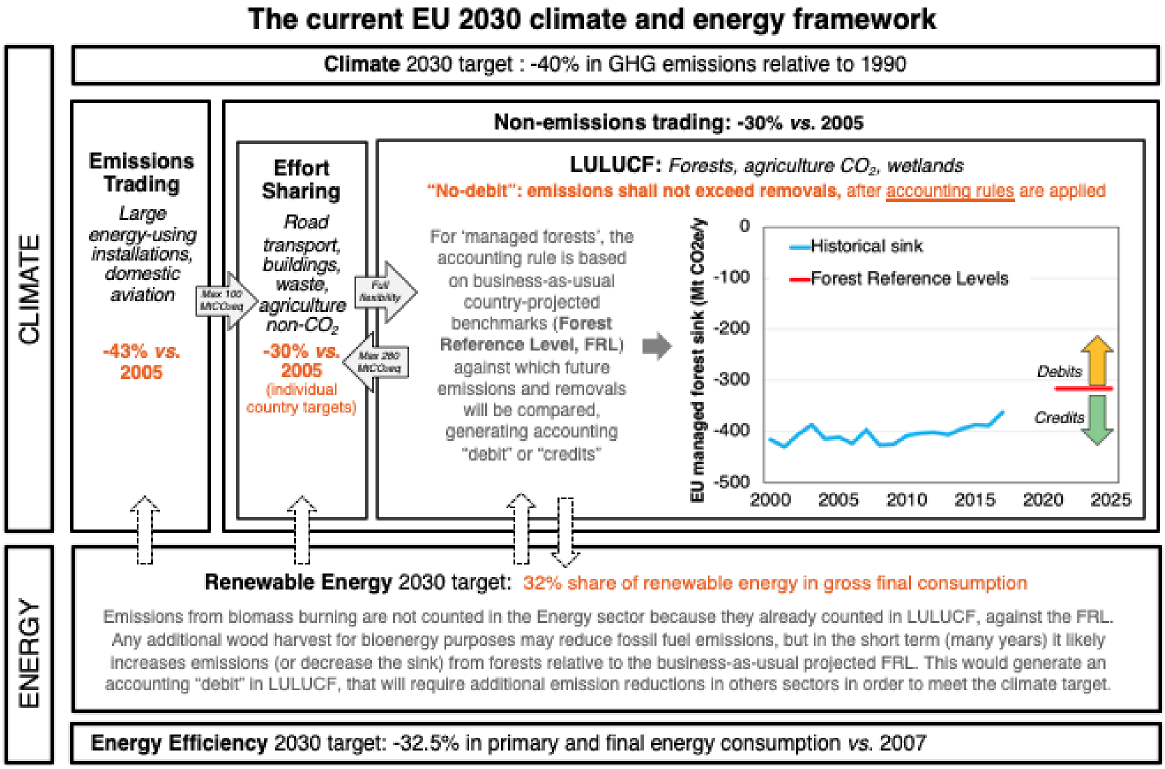
[32] The outcome of the FRL approach in the compliance period, either credits or debits, is essentially determined by the balance between the main drivers of the sink – forest growth and harvest – relative to what expected in the FRL. While the impact of management on forest growth is typically slow, on harvest it may be immediate. Therefore, leaving natural disturbances aside, harvest intensity relative to what expected in the FRL likely remains the main (but not the only) determinant of credits or debits in the short term.

[33] In many EU countries, forests age structure is largely determined by the heavy exploitation occurred until the first decades of the XX century. The large forest area with new trees that emerged after that heavy exploitation is now progressively reaching maturity.

The consequence of this approach is that any additional wood harvest for bioenergy purposes may help reduce fossil fuel emissions under the ETS or Effort Sharing sectors, but will also generate an accounting debit in LULUCF if it brings emissions beyond the FRL (i.e. if this extra harvest goes beyond the harvest expected in the FRL and is not compensated by an equivalent extra forest growth). Based on the above, the FRL is expected to have an indirect influence on the wood bioenergy demand, because any extra harvest that brings emissions beyond the FRL will have a "carbon cost" that will compete with other sources of energy.



For 'managed forests', the accounting rule is based on business-as-usual country-projected benchmarks (Forest Reference Level, FRL) against which future emissions and removals will be compared, generating accounting "debit" or "credits"

Emissions from biomass burning are not counted in the Energy sector because they already counted in LULUCF, against the FRL. Any additional wood harvest for bioenergy purposes may reduce fossil fuel emissions, but in the short term (many years) it likely increases emissions (or decrease the sink) from forests relative to the business-as-usual projected FRL. This would generate an accounting "debit" in LULUCF, that will require additional emission reductions in others sectors in order to meet the climate target.

Figure 30. Schematic representation of the current EU 2030 (EU27+UK) climate and energy framework[34], including the targets (orange text) for each legislation (from Grassi et al. in prep.).

The LULUCF sector (Regulation 2018/841), therefore, aims at reaching a certain future level of the forest sink (the projected Forest Reference Level, FRL), and this may be affected by the forest bioenergy policies (regulated by REDII) implemented to reach the Renewable Energy target. The plot represented within Box 2 (taken from Korosuo et al., 2020) shows for EU27+UK the historical sink from 'managed forest' under Regulation 2018/841 (including Harvested Wood product, HWP), the final FRLs for the period 2021-2025[35] and the accounted "debits" and "credits" that can be generated against the FRL.

Overall, the LULUCF regulation is an important step forward towards the "complete GHG accounting" of forest bioenergy that several studies suggested as necessary (e.g. Reid et al., 2019). In principle, this complete GHG accounting approach should also tend to allocate forest biomass toward climate-smart circular use of wood, such as long-lived wood products. That the Forest Reference Level approach for the post-2020 period represents a significant and worthwhile improvement on previous frameworks in terms of environmental robustness is demonstrated by numbers (see e.g. Fig. 13 in Korosuo et al., 2020) and confirmed by independent assessments (Matthews, 2020). Describing the EU climate framework as "failing to recognise that removing forest carbon stocks for bioenergy leads to an initial increase in emissions" (Norton et al., 2019) is a dated argument. This argument was largely true in the 1st compliance

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[34] https://ec.europa.eu/clima/policies/strategies/2030_en

[35] https://ec.europa.eu/clima/news/commission-sets-forest-reference-levels-delegated-act_en

period of the Kyoto Protocol (2008-2012, when most of bioenergy emissions could remain unaccounted), partly true in the 2nd compliance period of the Kyoto Protocol (2013-2020), but to a large extent it is untrue for the post-2020 period. The assumption of "carbon neutrality" of forest bioenergy does not apply to the whole EU climate and energy framework post-2020: REDII and EU Emission Trading Scheme assume zero-rating of emissions from biomass combustion, because the carbon impact of any change in management or wood use (including related to bioenergy) are fully reflected in each country's climate accounts, through the LULUCF regulation 2018/841.

Nevertheless, in practice the LULUCF regulation per se cannot guarantee a positive climate impact of bioenergy. Mismatch of policy incentives, complexity, poor communication among actors (state vs. private), infrastructural, institutional, and behavioural lock-in (Reid et al., 2019), as well as the need for robust accounting of the impacts of imported biomass, can still produce unintended climate outcomes. The implications of these risks and possible mitigating measures are discussed in section 5.3.2.

5.3.2 Potential improvements in the interface between EU REDII and EU LULUCF

As illustrated schematically in Figure 28, the various tools within the EU legal framework provide incentives towards different management goals for European forests, from incentivising forest bioeconomy to protecting the carbon sink and forest ecosystems. The resulting balance of these different pulling drivers will eventually define both the contribution of forests wood-based products to EU climate mitigation, as well as the resulting state of forests' health (Wolfslehner et al., 2020). As mentioned also in Section 5.2.1, it is natural that different stakeholders with different worldviews, including within the scientific community, have a preference for one driver or another. At the same time, many different equilibrium points are possible and acceptable within the socio-economic context of each Member State. However, if flaws appear within the governance tools, some of the drivers might pull the system towards unacceptable states in which, for example, the country-level climate mitigation goals are not reached, or the forest ecosystems are further degraded. Here, we highlight two interactions that might lead to these undesirable states with a focus on carbon mitigation output, and provide possible recommendations.

The first challenge is that, within the EU, different signals are sent to economic operators and to countries' governments. On the one side the EU ETS and the REDII, through the zero-rating accounting and by considering forest biomass as renewable, in principle incentivises economic operators to make an increasing use of forest bioenergy, thus stimulating the demand of wood. Additionally, by allowing forest bioenergy to contribute to the renewable energy targets and to be subsidized through national support schemes, REDII permits countries to support forest bioenergy as a way to meet their targets. On the other side the EU LULUCF accounting, by determining the level beyond which any additional domestic harvest (including for bioenergy) will be "fully paid" in terms of carbon (i.e. the FRL), in principle disincentivises countries to harvest beyond this limit, unless this is compensated by extra forest growth or unless the positive impact of using this extra harvest (i.e. reducing GHG emissions in other sectors) compensates its carbon price.

This conflict may lead to non-optimal governance choices: a high demand for forest bioenergy, even if accounted as "debit" under LULUCF, may create inefficiencies in the overall EU climate policies and potentially put the national climate targets at risk. The mismatch between policy incentives arises especially from the difference in target groups (economic actors vs. national governments, energy vs. forest experts) and the associated time horizons involved. These challenges easily lead to misunderstandings or imbalanced information, both in the scientific discussion and in the practical implementation of policies, which may end up in unintended outcomes. These risks are illustrated in the Box 3 through the "credit card" analogy.

BOX 3: Credit card analogy (from Grassi et al. in prep.).

A parent gives a credit card to his child, explaining that the card is charged in the family's bank account and that any expense beyond an agreed amount should be done only if it gives a benefit to the family. The main risk is that the child misuses this card, e.g. spending beyond the agreed amount in investments which give an immediate benefit to him but with a long payback time for the family - this would have short-term detrimental effects on the family's bank account.

Likewise, the forest biomass (credit card) from the country-level LULUCF sector (parent) may risk to be over-used beyond the FRL (agreed amount) on short-term benefits for the economic operators in REDII context (child), generating debits in the LULUCF GHG accounts (family's bank account). This, in turn, would risk jeopardizing the fulfilment of country's climate target.

To manage this risk, it is important that the parent is aware of the risks, communicates effectively with the child, and monitors his/her choices. The parent may decide to accept that a short-term benefit for the child generates an accounting debt in family's account – the key is being aware of this. Likewise, a country may accept that more harvest for bioenergy purposes occurs in its forests than the one projected in the FRL, as long as it is aware that this will likely generate an accounting debit in the LULUCF sector in the short term (many years to decades), and that it is able to monitor accurately over time the impact of this choice.

Available evidence suggests that at least some of these risks are real. For example, most of the latest National Energy and Climate Plans (NECP) do not include an adequate assessment of the potential impacts of expanding forest bioenergy on carbon sinks, biodiversity, water, and air pollution. Specifically, they often lack details on how to supply the required biomass, and if the planned use of forest bioenergy to help reach the renewable target is expected to generate accounted credits or debits under LULUCF. In other words, not all Member States seem yet fully aware of the need to consider jointly the climate and energy plans under REDII and LULUCF, or how it will impact biodiversity.

The need of a greater awareness of the bioenergy-LULUCF links should then be reflected in appropriate national policies, avoiding that financial incentives to the use of forest bioenergy shift the balance towards undesirable states (e.g. excessive use of forest biomass, leading to LULUCF debits). This, in turn, necessarily requires a timely and accurate monitoring of the use of forest resources: without reliably knowing how much and what type of forest biomass is used, no effective policy can be implemented. Based on the findings described in chapter 3, the current significant gap in data often represents a major obstacle for an effective governance of forest bioenergy policies at national scale.

In general, prioritizing residues and a cascade use of wood remains a key overarching principle for maximizing the positive climate impact of bioenergy and limit the risks in the bioenergy-LULUCF interface highlighted above. However, translating this principle into norms proved to be difficult. During the preparation of the REDII legislation, the possible regulation of forest bioenergy sources purely on the basis of wood feedstock categories (e.g., only residues or thinnings, no stumps, etc.) was discussed in detail. It was concluded that, given the wide variety of situations across Member States, it was difficult to univocally define and meaningfully implement such restrictions in an EU legislation – the risk would have been to complicate compliance without necessarily fostering further sustainability or biodiversity conservation (EU 2016)[36]. Nevertheless, qualitative criteria on bioenergy supply have been proposed, e.g. for forest management and wood utilization with low risks of increased GHG emissions compared to fossil fuels (Matthews et al. 2018) and of negative impacts on biodiversity and ecosystem condition (section 5.8). These criteria may help bioenergy operators and, consistently with

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[36] See pag. 48 of SWD(2016) 418, Part 4, where the impacts of 'Option 5' (i.e. the policy option which excluded the direct use of stemwood for energy) are discussed.

REDII[37], help Member States to define bioenergy-related policies and financial incentives that limit the risk of non-optimal (or negative) climate impacts of bioenergy.

Irrespective from market drivers, a moderate future increase in the production of harvested wood products at EU level may be expected because of forest age dynamics (Grassi et al. 2018 and Korosuo et al. 2020) and, in some circumstance, to reduce risks (or as consequence) of forest fires, pests and windstorms. The residues and the industrial by-products associated with these harvested wood products - along with wood from silvicultural operations specifically aimed at enhancing the quality of trees and the growth of the forest stands - may be meaningfully used for energy production, also contributing to the economic viability of forestry which is an integral element of Sustainable Forest Management. In any case, to avoid negative impacts on biodiversity and climate, the use of forest biomass for energy production should be carefully planned and scrutinised in terms of compliance with the REDII sustainability criteria and compatibility with the new EU 2030 and 2050 climate targets (through the impact on LULUCF accounting).

A second challenge is on the imported forest bioenergy. REDII largely relies on the fulfilment on the National Determined Contributions (NDCs) under the Paris Agreement. If a country has an NDC that includes LULUCF, then the import of forest biomass for energy purposes is allowed, because the associated climate impact will be reflected in the exporting country's climate accounts. This treatment of forest biomass is not different from the treatment of any other imported goods associated with emissions in the exporting country. For LULUCF, it can be argued that not all NDCs express similar levels of ambition on forests under the Paris Agreement, nor the same level of monitoring quality. To this regard, the efforts to increase the ambition and transparency of NDCs (including the need of progression over previously submitted NDCs) are being done under Paris Agreement. For countries not having and NDC or not having LULUCF within their NDCs, it is crucial that evidence is provided that carbon stocks and sinks are maintained or enhanced for any imported biomass, at both the national and the relevant subnational level.

5.3.3 De-toxifying the debate on carbon impacts of forest bioenergy

In order to de-toxify the on-going debate surrounding the role of forest bioenergy as a climate change mitigation option, we make the following recommendations:

- That the scientific community acknowledges the steps forward made on accounting for the carbon impacts of forest bioenergy as a prerequisite for a more constructive dialogue.
- That policymakers and scientists alike recognize that diverging values, worldviews, and ethical perceptions of natural resources and their management are a core part of the debate. These will not be solved by more scientific research, because science is a social endeavour where value-choices and judgements are inevitable. Transparency is key and cooperation with policymakers and co-creation of useful results should be welcomed.
- The contribution of science to the debate would be greatly enhanced by testing the robustness of the forest bioenergy regulatory framework, also through modelling of policy scenarios, identifying means to avoid worst case scenarios and to promote good governance aimed at fostering win-win pathways. Scientists could greatly improve their support to policymakers by embracing their role as honest brokers, for instance, addressing questions such as: 'under which conditions can this bioenergy pathway contribute to climate mitigation?'; and 'will the current regulatory framework stimulate such conditions, or oppose the conditions that provide the worst case?'

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[37] According to recital 94 of REDII, "For biomass fuels, Member States should be allowed to establish additional sustainability and greenhouse gas emissions saving criteria."

5.4 Status of forest biodiversity in Europe

This section presents a summary of the forest chapter of the MAES report Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment (Maes et al., 2020).

Forests are the largest terrestrial ecosystem in the EU covering around 38% of the land area. The current condition of forest ecosystems in the EU is the result of natural and human-driven pressures taking place since the mid-Holocene. Nowadays, in the EU only around 2%—4% are primary forest undisturbed by man, whereas 89% are semi-natural forests. The rest are plantations.

Forest area has increased in the EU in the last decades. It gained 13 million hectares in the period 1990-2015 in the EU due to both natural processes and to active afforestation. This does not necessarily mean that the condition of forests in Europe is good. The major proportion of EU forests (84%) are considered Forest Available for Wood Supply – FAWS (see also Chapter 4 for the mapping of forest biomass in FAWS).

Around 14% of EU forests are protected for biodiversity. EU forests are exposed to a range of natural and human-driven pressures pointing towards degradation. Direct and indirect effects of changes in climate suggest degradation in six indicators of the MAES assessment in the long term or the short term. In addition, pollutants remain a concern for EU forests even if the trends point in the right direction. Moreover, invasive alien species (IAS) affects around 44% of the EU forest area. Finally, tree cover loss due to several drivers (wildfire, storms, harvesting) has been increasing notably.

Effects of pressures on forest condition are evident. Indeed, one out of four trees of the ICP Forests survey shows defoliation levels indicating damage. Not to mention that the trend points towards increasing defoliation. Likewise, other functional parameters such as evapotranspiration suggest changes in ecosystems consistent with an amplification of warming through the water vapour feedback and changes in water resources availability.

In contrast, some condition indicators show trends towards improvement, for example structural indicators such as forest area, biomass volume and dead wood. Likewise, ecosystem productivity is increasing, and the pressure represented by forest land taken by artificial structures is decreasing. However, forest soil loss continues to take place even if at a slower rate. Regarding biodiversity indicators, the abundance of common forest birds did not show significant changes in the long-term period. Nevertheless, the short-term trend suggests improvement.

In summary, the MAES assessment indicates that 47% of EU forest land is exposed to three or more drivers of degradation, 20% to four or more, and only 20% of forest land is exposed to fewer than two drivers of degradation.

The Habitats Directive EU-level assessment of the conservation status of 81 forest habitats concluded that 14% are in good (or favourable) conservation status (EEA, 2020). The remaining habitats are in poor status (54%), bad status (31%) or unknown (1%). The assessment concludes the general bad status of the forest habitats and species listed in the Habitats Directive with little progress towards good conservation status. In addition, the assessment indicates that forestry is the dominant pressure reported for most of the forest habitat types.

Forest habitats monitored under the Habitats Directive cover 28% of the EU's forest area. That means that the remaining 72% of forests is not monitored under this Directive. However, the MAES assessment mentioned above assessing the entirety of EU's forest shows numbers that point in the same direction as the Member States' reporting under the Habitats Directive.

These findings, considered in the perspective of the projected impacts of climate change, its indirect effects, the effects of pollutants, and the foreseen increased demand of forest resources, e.g. for renewable energy (Jonsson et al., 2018), should be considered in the perspective of a coordinated response at EU level looking at the synergies and trade-offs of different policy objectives.

5.5 Responses of the forest-based sector to changes in bioenergy demand

Given that European forests (but not only) are already under significant stress, it is crucial to understand how an increased demand for biomass for bioenergy, in synergy with other drivers, might affect forest management to evaluate whether this might place additional pressures on forest ecosystems.

The analysis in chapter 3 have allowed us to describe with some detail the input mix of EU forest bioenergy and the related uncertainties. As we have seen, 49% of the woody biomass used for energy comes from secondary sources, 37% from primary sources (i.e. directly from the forest), and 14% is not categorized in the reported statistics, so it could either be primary or secondary.

Regarding primary sources, the coppice forest management system plays an important role in providing relevant feedstocks for bioenergy, especially in Southern EU MS, where 32% of the forest area is coppice, mainly managed (when managed) for bioenergy purposes.

Figure 31 shows a simplified mapping of potential interactions between increased demand for forest-bioenergy and responses in the whole forest-based sector. This complex system includes multiple economic sectors (land rents, forest, materials, energy) and social actors, and presents many causal linkages and feedback loops, leading to multiple environmental impacts. For instance, the responses of the forest-based sector are influenced by other policy objectives (as described above) and eventual Regulations (e.g. bioenergy sustainability criteria), and by the impacts of climate change on future growing rates of forests and on the frequency and magnitude of natural disturbances. Social factors such as forest owners' behaviours and cultural values also have (Dorning et al., 2015; Thiffault et al., 2016). These mediating factors materialise in price signals for forest commodities and land which affect the responses from the forest-based sector.

We do not claim these feedbacks as 'likely' to take place, but rather as 'possible' responses; indeed Giuntoli et al. (2020b) distilled these interactions by reviewing mainly bioenergy literature. They summarise the potential responses in three main categories affecting: 1) forest management practices, 2) consumption patterns, or 3) the land use.

The first type of responses concerns forest management practices and their consequences for in-situ carbon stock and sink. A typical response assumed in most of the existing literature (e.g. (Agostini et al., 2014; Giuntoli et al., 2015; Holtsmark, 2013)) is *increased extraction* of primary forest sources, including actions such as expanding the removal of logging residues, raising pre-commercial and regular thinning intensity, and increasing the harvest intensity on commercial stands by shortening harvest rotations (Egnell and Björheden, 2015; Pohjanmies et al., 2017). Additionally, areas of forest currently not under commercial management due to unfavourable socio-economic conditions or forest owners' choices, may begin to be commercially logged (*increased area of active management*). Finally, *increased growth* responses aim to improve forest productivity to increase production of wood. These include, for instance: applying fertilization, shifting to fast-growing plantations, replanting with more productive hybrid tree species, and enhancing the C-stock of degraded or abandoned stands (de Jong et al., 2017; Egnell and Björheden, 2015; Law et al., 2018; Matthews et al., 2018; Nilsson et al., 2011).

The second response concerns consumption patterns of wood products. If additional demand for wood bioenergy results in higher prices for Harvested Wood Products (HWP), the forest-based sector will respond either by an increase in wood harvest or by displacing part of the existing material use of wood to energy (Nepal et al., 2019). This could lead to: i) elastic decrease in the demand for traditional wood products, and/or ii) a market leakage, whereby part of the feedstock used for materials would be sourced from other geographical locations with its associated impacts (Jonsson et al., 2012). This response is important since Harvested Wood Products (HWP) contribute to climate mitigation both by storing carbon while in use, and by substituting other non-wood materials and products which might be characterised by higher carbon footprints (Figure 33) (Johnston and Radeloff, 2019; Leskinen et al., 2018).

Finally, forest bioenergy demand may also impact land-use and stimulate responses such as afforestation, reduction of deforestation rates, as well as restoration of degraded or unproductive forestland, such as abandoned coppice forests (Abt et al., 2014; Buckley, 2020; Khanna et al., 2015; Parish et al., 2017).

Indirect feedbacks can influence results in unexpected ways. For instance, increased demand for wood bioenergy could translate into increased demand for sawmill by-products and subsequently stimulate increased harvests and transformation of sawlogs (Jonsson and Rinaldi, 2017). On the other hand, increasing the relative attractiveness of energy from wood may reorient forest management objectives from the production of quality industrial logs towards higher biomass outputs, thus reducing long-term supply of sawtimber in favour of smaller-diameter products, with potential wide-ranging consequences on the wood industry and on ecosystems.

The changes listed above have very different timeframes for implementation and effects, as well as different economic returns and incentives. Collecting a larger share of logging residues and expanding areas of pre-commercial thinnings are short-term options for increasing bioenergy production (Egnell and Björheden, 2015), whereas fertilization, and afforestation increase the supply of biomass in a longer time frame. Further, increasing forest growth will reap rewards for forest owners only in the long term, and the profitability of these management strategies is thus often low (Egnell and Björheden, 2015).

The direct and indirect carbon impacts of these responses and of the bioenergy produced can be calculated through different approaches that should be chosen accordingly, depending on the goal of the assessment. The next section elucidates this concept.

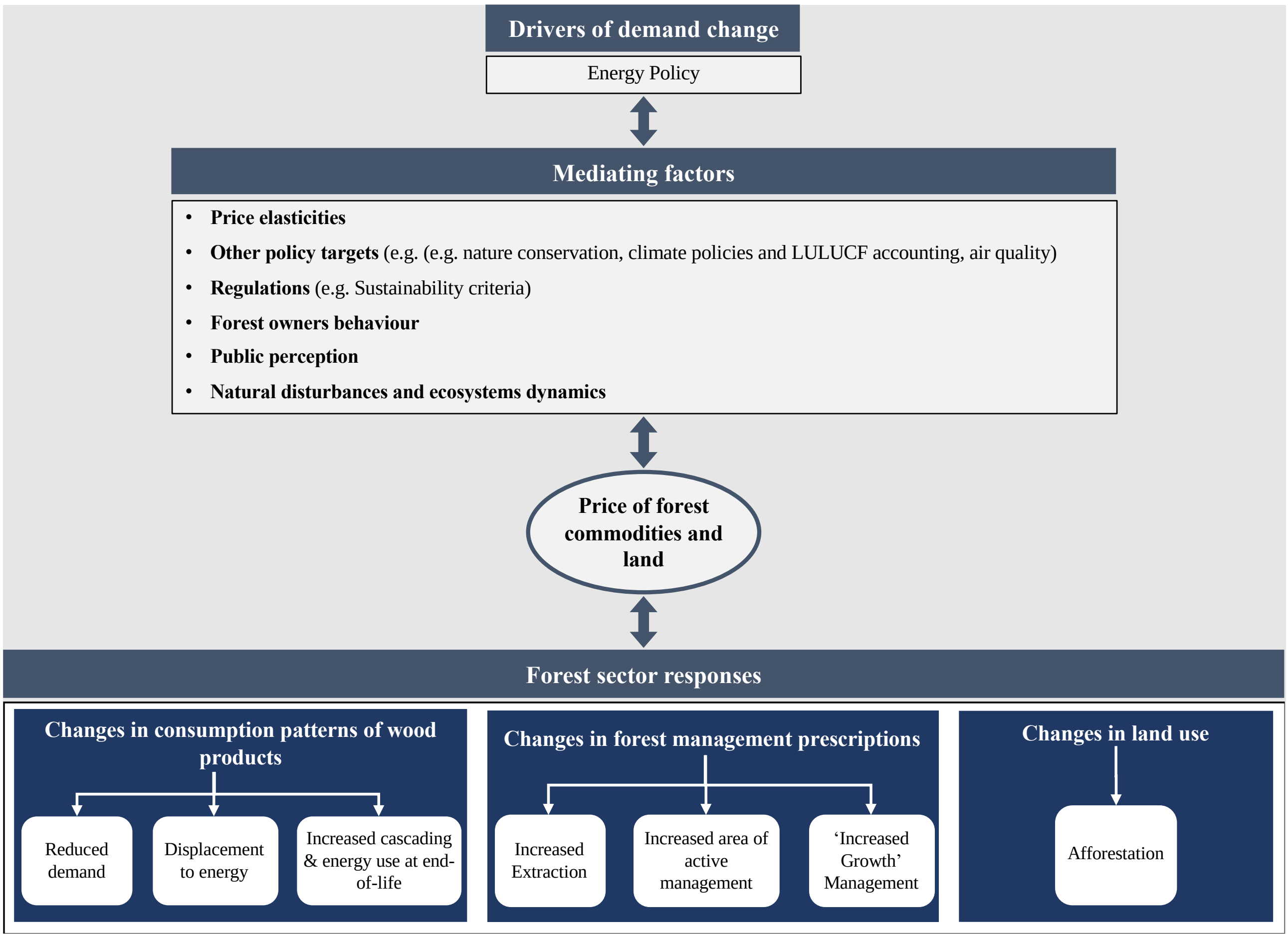


Figure 31. Schematics of the link between the drivers of change of demand wood-based bioenergy, potential changes in the forest-based sector and their link through mediating factors. Source: Adapted from (Giuntoli et al., 2020b)

5.6 Carbon accounting of forest bioenergy through Life Cycle Assessment: lessons learnt and available qualitative assessments

Life Cycle Assessment (LCA) has become a key tool in pursuing sustainable production and consumption patterns over the years and it has also been increasingly integrated into the policymaking process, either at the stage of policy design and impact assessment, or directly into legislative documents (Sala et al., 2016).

Even though LCA is a standardized methodological approach, the ISO and other standards available leave abundant freedom to the practitioners to choose the modelling framework they deem relevant. Thus, the interpretation phase is crucial to make sure that the results are consistent with the defined goal and scope, and that the conclusions presented are robust. However, too often both practitioners and decision makers have overlooked this fundamental phase of the LCA and have drawn conclusions which are either not supported by the study performed or go well-beyond what the limitations of the study would allow (Agostini et al., 2020).

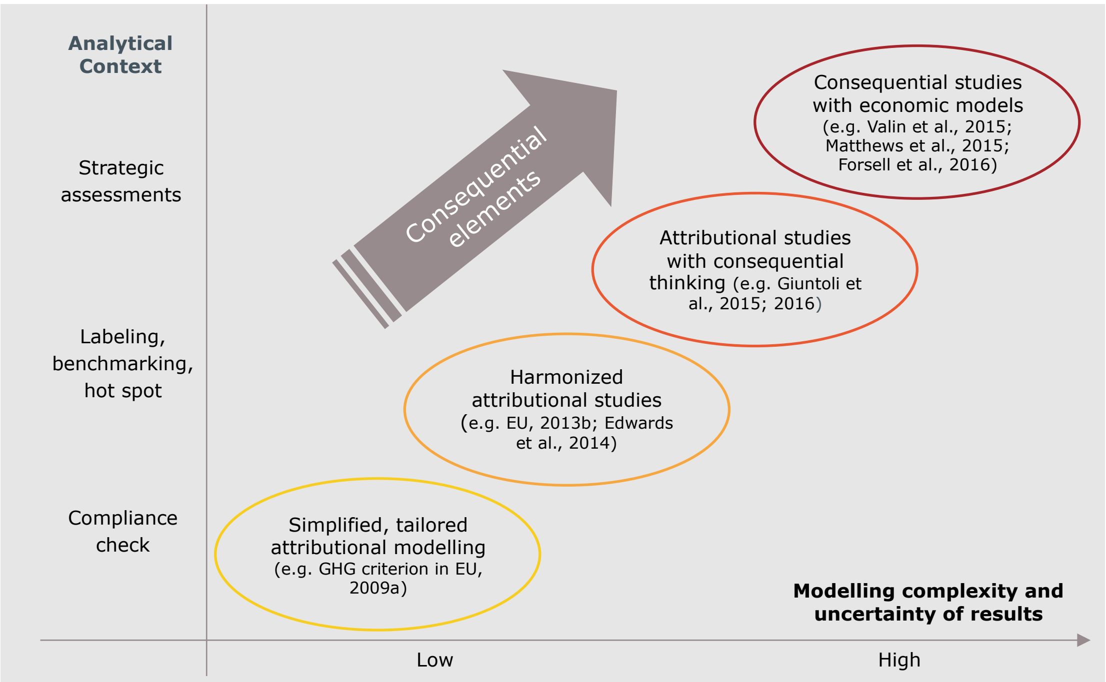


Figure 32. Examples of LCA studies used for policy support and LCA methodology implementation in EU policy, classified according to analytical context and modelling complexity. Source: (Giuntoli et al., 2019)

Figure 32 illustrates the proper analytical context in which different modelling approaches should be, and have been, used in several examples relevant for bioenergy policy in the EU.

LCA models that support the implementation of specific legislative instruments respond to the specific requirements defined within the instrument itself. They should be easy to calculate, well-defined, use a well-specified, easily accessible and stable inventory, and be of general validity across the temporal and spatial scales covered by the legislation (Plevin et al., 2014). This is clearly the case for the EU Renewable Energy Directive GHG criterion (Directive 2018/2001, Art. 29(10)). The purpose of the methodology defined in the RED and REDII is to benchmark various bioenergy supply chains and to promote the more efficient ones. It is not the scope of the methodology to represent the actual GHG emissions associated to each pathway, since biogenic-C and market-mediated effects are explicitly excluded.

On the other hand, LCA models that assess the impacts of strategic policy decisions are often used during the policy formulation and impact assessment stages. Studies that aim to assess large-scale impacts of policies on the overall economy usually rely on economic models that cover multiple sectors of the economy, large geographic scales, and all relevant ecological processes (Plevin, 2017). Such studies have indeed been undertaken in the past to support the impact assessment of EU bioenergy policy options (e.g. Forsell et al., 2016; Matthews et al., 2015) and focus on capturing as many interlinked consequences and feedback loops as possible, across scales, sectors, and environmental burdens, to avoid unintended consequences of policy decisions. Similar exercises are carried out frequently, usually thanks to various Integrated Assessment Models (IAMs), in many other contexts, such as to calculate GHG emissions reduction trajectories in IPCC Assessment Reports, to study possible interactions with sustainable development goals (van Soest et al., 2019), to evaluate potential strategies for conservation of ecosystems and species (Harfoot et al., 2014), etc. Figure 33 illustrates the main pools and flows affecting the carbon balance of forest bioenergy (Birdsey et al., 2018) that should be included in systemic, strategic assessments of forest bioenergy scenarios. The contribution of forest bioenergy to overall carbon emissions results from the balance between responses taking place in-situ, i.e. the changes in forest carbon stock and sink, and responses ex-situ, such as potential substitution of other energy sources and of carbon-intensive materials (such as construction materials and biorefinery products). Additionally, effects on land use may have a significant impact on the final balance. These studies usually require interdisciplinary teams, long timeframes and advanced analytical tools. Cooperation between decision makers and scientists is crucial for the creation of useful scenarios as well as to include multiple worldviews within the modelling assumptions. The downside of this approach is that attribution to a single product, or pathway, is often complicated, and what is assessed is actually the impact at large of a policy tool or the impacts of a defined scenario (e.g. Shared Socioeconomic Pathways for IPCC assessments).

A rare, but important study by Matthews et al. (2015) ran a systemic analysis which included all the elements above, but was also able to disaggregate the findings on a product-based perspective. The study found that the EU GHG targets could be achieved with different levels of bioenergy penetration, but when looking in detail at the contribution by each energy source to the overall GHG emissions (i.e. through a product-based analysis), they found that forest bioenergy could have a positive or negative GHG impact depending on the type of feedstock considered and the forest management practices assumed to take place in the future. This is a similar distinction as reported earlier in section 5.3 between the overall EU GHG accounting, and the specific carbon impact of each bioenergy pathway, the two concepts are not necessarily linked.

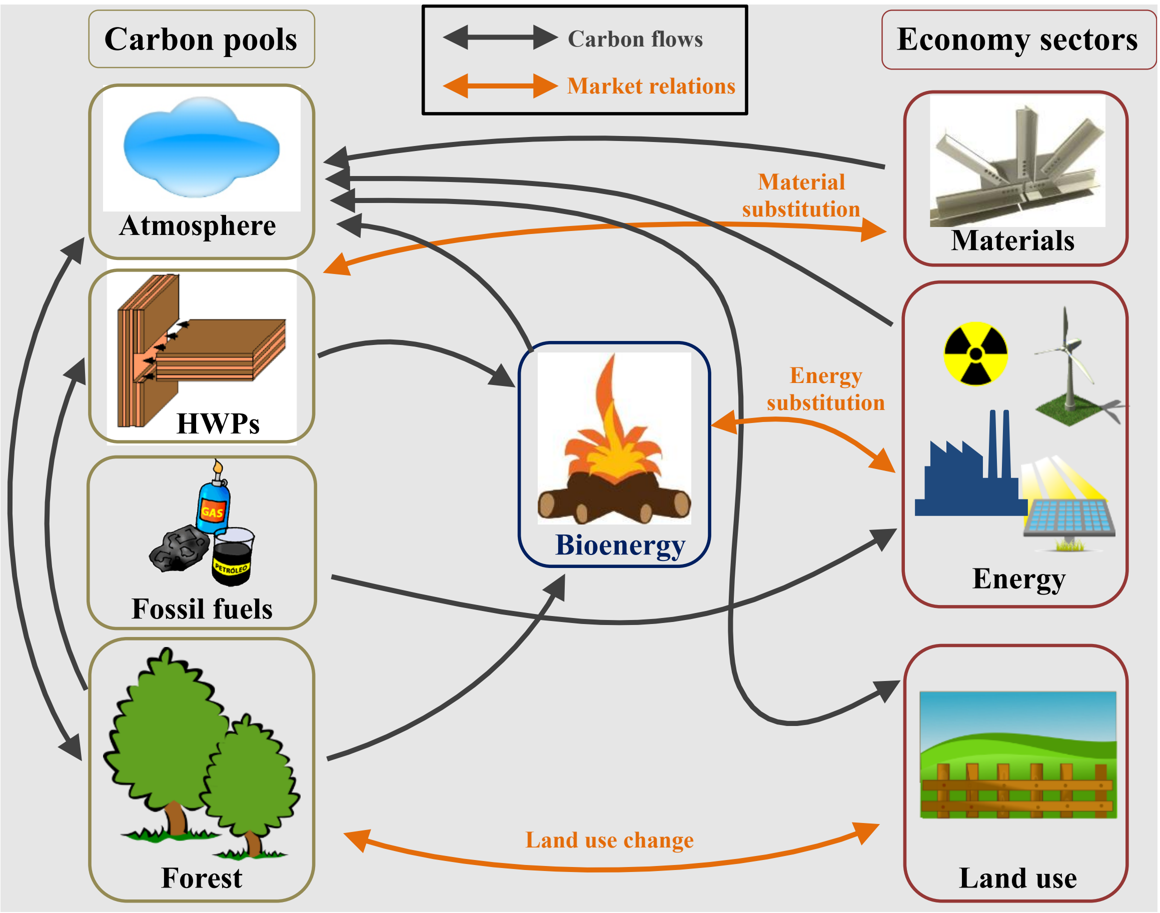


Figure 33. Representation of carbon pools, economy sectors and flows to be considered in an LCA study of forest bioenergy.

The approach taken in this report is an intermediate one between the two extremes described above. It is based on attributional modelling so that impacts can be attributed to a single bioenergy pathway, but it accounts for biogenic-C and for the counterfactual use of biomass. This method is the most appropriate for the goal of this study.

No new calculations are carried out in this report, but rather we largely rely on the results provided by Agostini et al. (2014) and reported in Table 5. These results remain valid today and they formed an important part of the evidence-basis used to design the EU REDII (EU, 2016a). Results of carbon impacts of other bioenergy pathways have also been collected (contact authors for full list).

It is important to recall some fundamental assumptions behind the results in Table 5:

- A baseline or counterfactual, i.e. "the hypothetical situation without the studied product system" (Soimakallio et al., 2015), is defined for each pathway and reported in detail in section 5.9;
- Biogenic-C is fully accounted both for the counterfactual and the bioenergy pathway;
- The qualitative impacts in Table 5 are evaluated over different temporal scales because of the time-dependent nature of the trends involved. A detailed discussion is given in (Agostini et al., 2014), however we repeat here the basic concepts for clarity. In this study the term ‘carbon debt’ indicates the phenomenon by which the bioenergy pathway may produce higher carbon emissions compared to the fossil counterfactual/reference chosen for comparison, and the term ‘payback time’ is the time needed for the carbon debt to be repaid and for the bioenergy system to begin providing carbon mitigation. Once the payback time is reached, though, the bioenergy system still has contributed to global warming more than the fossil fuel system. Figure 34 illustrates these concepts. At the payback time, the cumulative emissions of the fossil and bioenergy systems are the same. However, the bioenergy system will have contributed a higher GHG concentration in the atmosphere, thus leading to higher radiative forcing over a period longer than the payback time. The atmospheric carbon parity point is the point in time when bioenergy may be considered carbon neutral. This point is reached when the additional emissions caused by the bioenergy system until the payback time equal the emissions saved by substituting fossil fuels combustion. At the moment in time when the savings (L1) equal the emissions due to bioenergy (L2) then the atmospheric carbon parity point is reached.
- Additionally, the results in Table 5 are differentiated over the fossil energy source used as a comparator because the carbon intensity of the different fossil fuels will greatly influence the payback time.
- Finally and importantly, the results in Table 5 are evaluated on a ‘ceteris paribus’ perspective, in the sense that market-mediated effects associated with a bioenergy pathway are explicitly excluded. This means that, for instance, rebound effects in the energy market are excluded (Leturq, 2020), indirect effects on wood products markets are excluded etc. As a consequence, these results should be interpreted as representing mainly the impact of the production of a relatively small quantity of the product (e.g. 1 MJ) and not representing the impacts of a large-scale deployment of bioenergy which would then affect installed production capacities and lead to many of the market-mediated effects mentioned above.

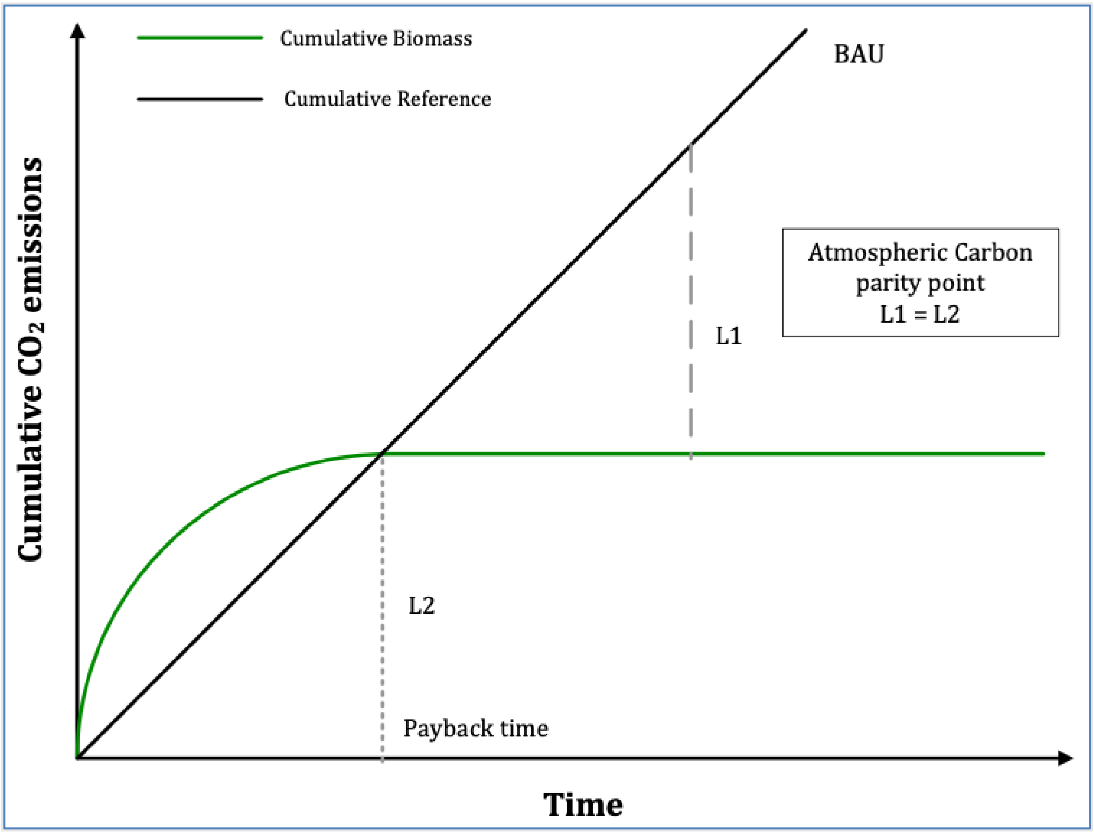
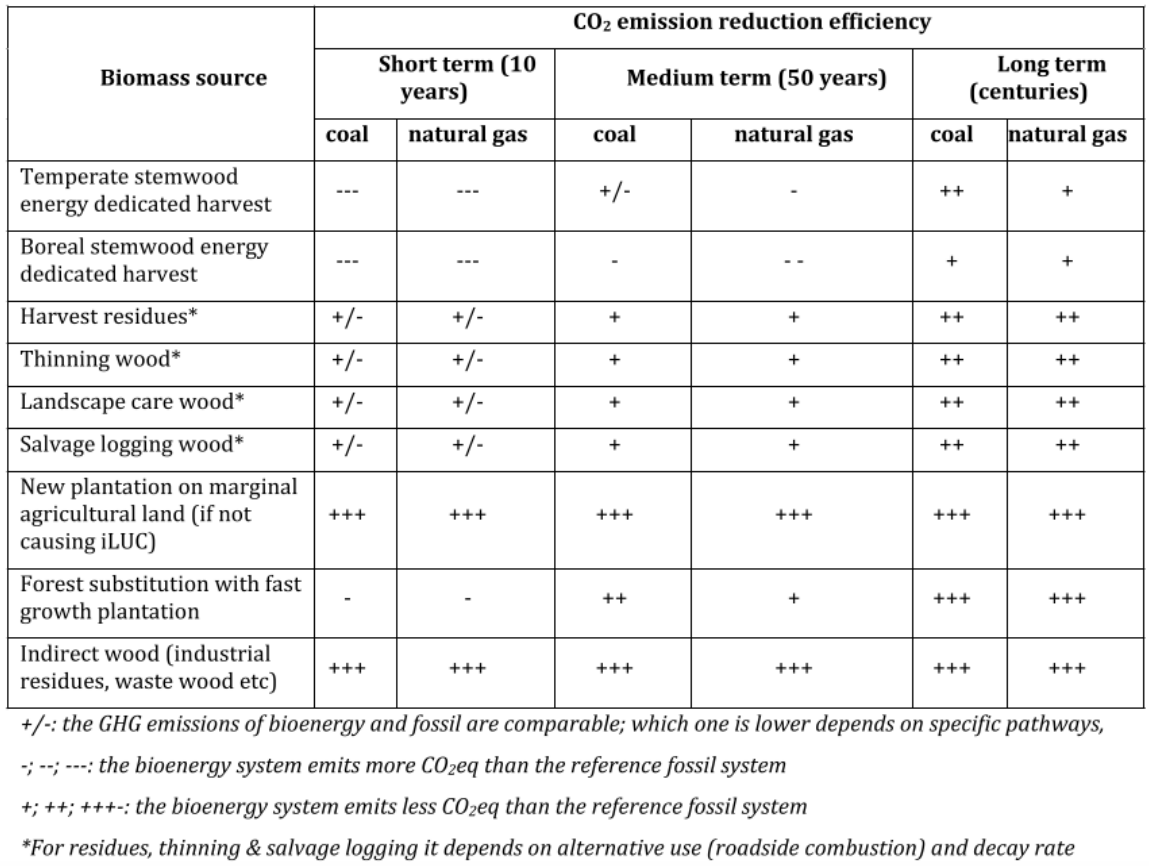


Figure 34. Visual description of payback time and atmospheric carbon parity point. Green Line: drop in the forest carbon stock due to bioenergy production; Black line: accumulated reduction in carbon emissions from substitution of fossil fuels. Source: *(Agostini et al., 2014)*

Table 5. Qualitative evaluation of carbon emission reduction of several forest bioenergy pathways compared to two different fossil sources and on three different time frames. Source (Agostini et al., 2014)



Biomass source	CO₂ emission reduction efficiency					
	Short term (10 years)		Medium term (50 years)		Long term (centuries)	
	coal	natural gas	coal	natural gas	coal	natural gas
Temperate stemwood energy dedicated harvest	---	---	+/-	-	++	+
Boreal stemwood energy dedicated harvest	---	---	-	- -	+	+
Harvest residues*	+/-	+/-	+	+	++	++
Thinning wood*	+/-	+/-	+	+	++	++
Landscape care wood*	+/-	+/-	+	+	++	++
Salvage logging wood*	+/-	+/-	+	+	++	++
New plantation on marginal agricultural land (if not causing iLUC)	+++	+++	+++	+++	+++	+++
Forest substitution with fast growth plantation	-	-	++	+	+++	+++
Indirect wood (industrial residues, waste wood etc)	+++	+++	+++	+++	+++	+++

+/-: the GHG emissions of bioenergy and fossil are comparable; which one is lower depends on specific pathways,

-; --; ---: the bioenergy system emits more CO_2eq than the reference fossil system

+; ++; +++-: the bioenergy system emits less CO_2eq than the reference fossil system

**For residues, thinning & salvage logging it depends on alternative use (roadside combustion) and decay rate*

5.7 Forest bioenergy: impacts on biodiversity and ecosystems' condition

In this section we focus on the potential pressures that bioenergy demand may place on forest ecosystems' condition and biodiversity. The ecological literature is rich with information that should be integrated within the bioenergy literature and properly communicated to decision makers. This is the main goal of this section.

5.7.1 Biodiversity & climate change trade-offs

Assessing the impact of forest bioenergy on ecosystems' condition in general, and in particular on biodiversity, is complicated because bioenergy pathways can exert multiple pressures on ecosystems and biodiversity and at the same time alleviate others. This creates an intricate matrix of trade-offs and synergies between forest bioenergy production and biodiversity and the condition of forests. Figure 35 presents a simplified model of the potential pressures created by forest bioenergy production on local and global biodiversity. At the local level, intensified forest management to produce additional biomass can increase pressures on forest ecosystems. Similarly, land use change associated to afforestation can drive positive or negative impacts on local biodiversity. Additionally, the supply chain to produce bioenergy commodities is associated to the emission of pollutants which may contribute to acidification, eutrophication, and further climate change. Nevertheless, at the global level, climate change in itself is a major driver of biodiversity loss, therefore the overall benefit to the ecosystems and biodiversity might still be higher from global climate change mitigation if compared with the local level effects mentioned above.

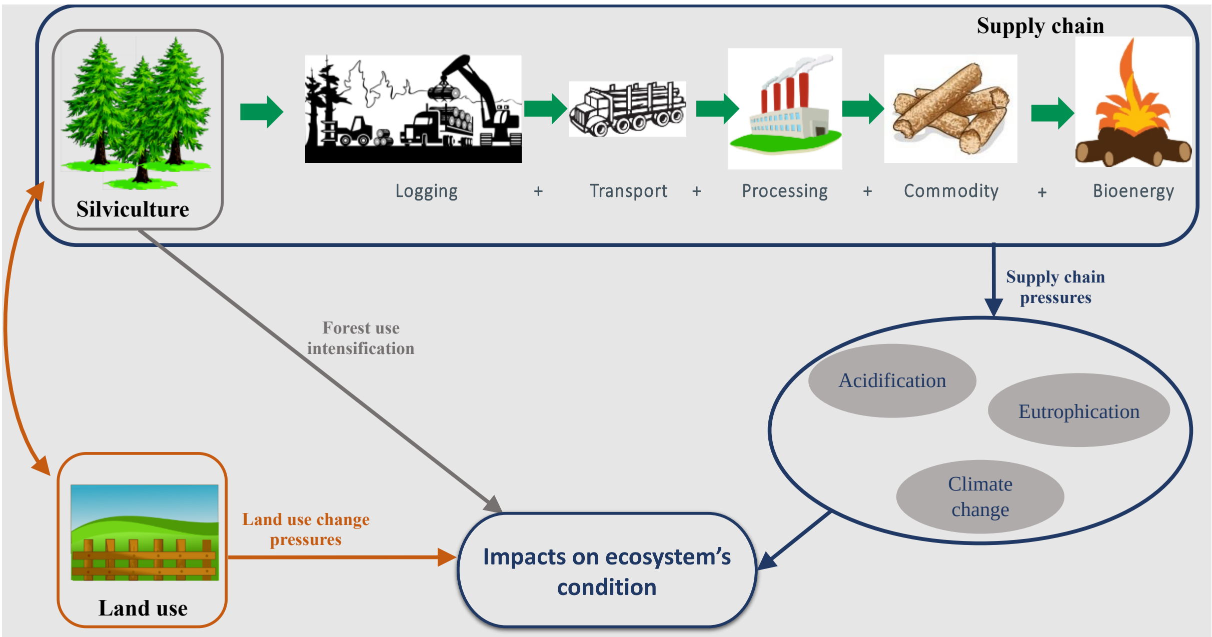


Figure 35. Schematic of pressures on biodiversity and ecosystems' health arising from forest bioenergy supply chains. Especially, we can differentiate among local-level direct pressures from land use change and land occupation (i.e. forest management) and other pressures due to the supply chain emissions, such as acidification, eutrophication and global climate change.

The trade-off between potential long-term advantages from climate change mitigation and short term, local ecosystems' degradation is very difficult to quantify. Therefore, under the precautionary principle, we exclude it from this analysis, assuming that we should not evaluate hypothetical long-term benefits versus short-term effects on ecosystems.

Instead, we focus our analysis on potential pressures on local biodiversity and ecosystems from land use changes and forest management intensification in order to highlight potential pathways causing negative environmental trade-offs, or "bio-perversities"[38] (Lindenmayer et al., 2012).

5.7.2 How to assess impacts on ecosystem condition and biodiversity?

While Life Cycle Assessment is a tested and proven methodology to account for environmental impacts associated to products and supply chains, the recent review by Crenna et al. (2020) highlights how, despite recent advancements, unfortunately no methodology exists that is fully mature and developed to capture the impacts of products on all attributes of biodiversity or ecosystem condition appropriately and completely.

In the absence of a clear standardized methodology to be followed, we rely on established conceptual frameworks to provide a qualitative assessment of the impacts of forest bioenergy on ecosystem condition. Specifically, we rely on the work of MAES, State of Forest Europe, and IPBES assessment frameworks. Even though these frameworks are mainly aimed at assessing a set of indicators for ex-post monitoring of the condition of ecosystems, the conceptual frameworks can also be used to classify the impacts (or 'outcomes') of the interventions assessed.

Figure 35 illustrates the assessment framework used in this chapter. From the top, we consider the potential pressures on forest ecosystems resulting from an increased demand of forest resources for bioenergy (as explained in section 5.5). Among these potential responses we have chosen the following forest management practices to be investigated in depth:

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[38] Lindenmayer et al. (2012) (Lindenmayer et al., 2012) defined bio-perversity as "*the negative biodiversity and environmental outcomes arising from a narrow policy and management focus on single environmental problems without consideration of the broader ecological context*".

1. Increased removal of different types of logging residues;
2. Afforestation of different types of non-forest land with different types of forests;
    a. As a sub-category: conversion of naturally regenerated forests into plantations.

We align our terminology with what is used in systematic reviews, and we define these management practices as the ‘interventions’ assessed.

As described in section 5.5, several additional forest management interventions can be considered to supply biomass for bioenergy. These were not looked at in details for several reasons. Firstly, because many of these interventions are part of more ‘traditional’ forest management practice which has already been the subject of extensive literature investigation (see e.g. Chaudhary et al., 2016). Secondly, many of those interventions do not provide ‘additional’ biomass but rather rely on simply increasing extraction levels (e.g. shortening rotations) or on displacing materials from other sectors. In the first case, the impacts on carbon are known to be negative for a long payback time (see Table 5) so there was not much added value in looking at potential trade-offs. In the second case, indirect effects are very important and should be looked at through a more systemic perspective compared to the product-based approach taken in this report. Our findings should not be interpreted to capture the whole range of possible risks and benefits associated to forest management interventions linked to bioenergy. Across this report we refrain from discussing any intervention that we have not investigated in details; however, assessing certain cases might be fairly straightforward. For instance, the harvest of native, mature, high-biodiversity value trees for energy use would be a clear lose-lose option. On the other hand, coppice forests are particularly important in Mediterranean countries, they provide many ecosystem services, have relevant socio-economic functions in many rural areas and are mainly utilised for bioenergy. However, in large areas coppices are no longer managed or completely abandoned, resulting in old or overgrown declining stands. In these cases, it is suggested to encourage active forest management, that would enhance the capacity of these ecosystems to store carbon and supply services. Depending on local considerations the preferred option could be active conversion to high forest, or coppice restoration (see Section 5.9.2).

The three interventions above were chosen because they were found by Giuntoli et al. (2020b) to be key assumptions in modelling studies finding forest bioenergy as an effective option for carbon emissions reduction. They found that these studies often assume that growing bioenergy demand would increase prices for woody biomass thereby stimulating active forest management, with changes aimed at improving forest productivity (i.e. ‘increased growth’ responses in section 5.5) or an increased collection of forest residues. Several studies also assume that increased bioenergy demand will drive afforestation efforts (e.g. Galik and Abt, 2016; Khanna et al., 2015). The interventions chosen aim to supply ‘additional’ biomass (Lemprière et al., 2013; Searchinger et al., 2009), i.e. growing biomass that would not be produced in the absence of bioenergy demand (thus enhancing the terrestrial carbon sink) or using biomass, such as residues and wastes, that would otherwise decompose or burn on site (thus reducing GHG emissions to the atmosphere) (Blanco et al., 2015).

Even though Giuntoli et al. (2020b) also found that, until now, many of these responses have not been stimulated as a direct consequence of bioenergy expansion, they are still high on the agenda of potential mitigation strategies (IPCC, 2019) and could take place as a direct or indirect effect of increased demand of forest biomass (incl. for bioenergy). Indeed the recent EC communication “Stepping up Europe’s 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people" (EU, 2020) explicitly suggests that afforestation should be promoted as a source of biomass for bioenergy[39].

However, while the carbon impacts of all these interventions have been investigated in-depth, we find that a detailed synthesis of their impacts on biodiversity is currently lacking from the bioenergy literature.

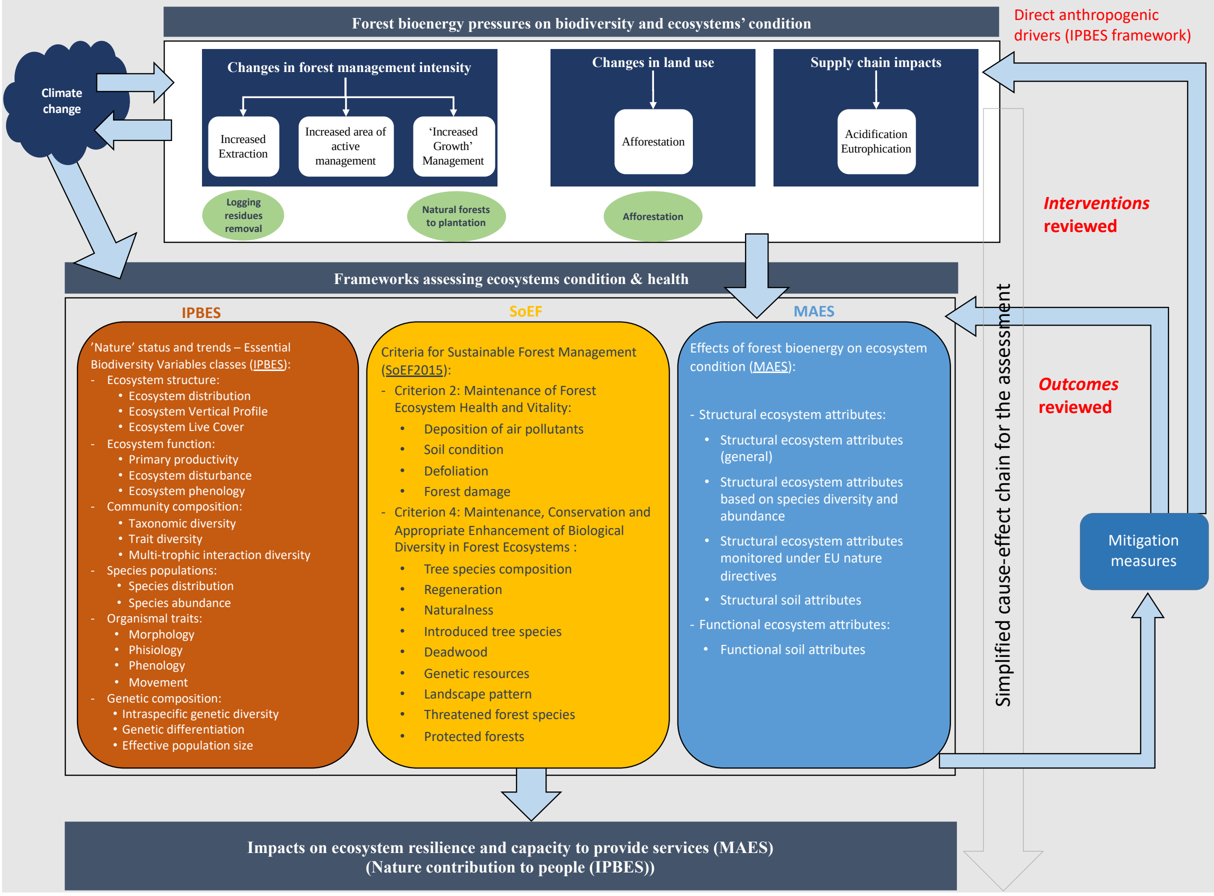

Figure 36. Assessment framework of the literature review in this chapter.

For our assessment, we rely on a literature review. For each paper we assessed the impact of these interventions on various attributes of biodiversity and ecosystem conditions as defined by the MAES (Maes et al., 2020) and IPBES frameworks (Díaz et al., 2015). Impacts on these attributes are defined as the 'outcomes' of the intervention and are defined relative to a counterfactual, or comparator. The details of the initial literature search and the assessment for each paper are provided in the Annex. The specific counterfactuals used in the qualitative synthesis of results are reported later in Table 11.

Specifically, based on the MAES framework we assessed potential impacts on:

1. Structural ecosystem attributes (general)
2. Structural ecosystem attributes based on species diversity and abundance

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[39] Impact Assessment (SWD(2020) 176) of the Communication COM(2020) 562, on Pag. 122: << *Synergies and risks related to the biodiversity strategy exist. The implementation of the Biodiversity Strategy is coherent with significant GHG reductions in the sector. While biomass needs for the energy system do increase, these are limited up to 2030 but increase afterwards.* ***Producing this increased biomass supply through sustainable forestry, biodiverse rich afforestation and an overall reasonable deployment of sustainable energy crops could reconcile climate and biodiversity objectives.***>>

3. Structural ecosystem attributes monitored under EU nature directives
4. Structural soil attributes
5. Functional soil attributes

Further, we expand on the MAES framework with the IPBES framework of Essential Biodiversity Variables (EBV) (Pereira et al., 2013), as illustrated in Table 6.

Table 6. Essential Biodiversity Variables Classes and examples of indicators. Source: (Pereira et al., 2013)

	EBV Classes	**EBV examples**
1	Ecosystem structure	Ecosystem distribution Ecosystem Vertical Profile Ecosystem Live Cover
2	Ecosystem function	Primary productivity Ecosystem disturbance Ecosystem phenology
3	Community composition	Taxonomic diversity (species richness, species assemblages)
		Trait diversity
		Multi-trophic interaction diversity
4	Species populations	Species distribution
		Species abundance
5	Species traits	Morphology Physiology Phenology Movement
6	Genetic composition	Intraspecific genetic diversity Genetic differentiation Effective population size

5.7.3 Synthesis and assessment of trade-offs

In practice, the goal of the assessment was to attempt to fit each intervention assessed in one of the four categories in Figure 37. A similar assessment framework was presented by Paterson et al. (2008).

Pathways in the first and fourth quadrants are relatively clear situations in which trade-offs are not evident, and should thus clearly be a target for governance measures; in the sense that pathways in quadrant 1 should be incentivised, while pathways in quadrant 4 should be discouraged.

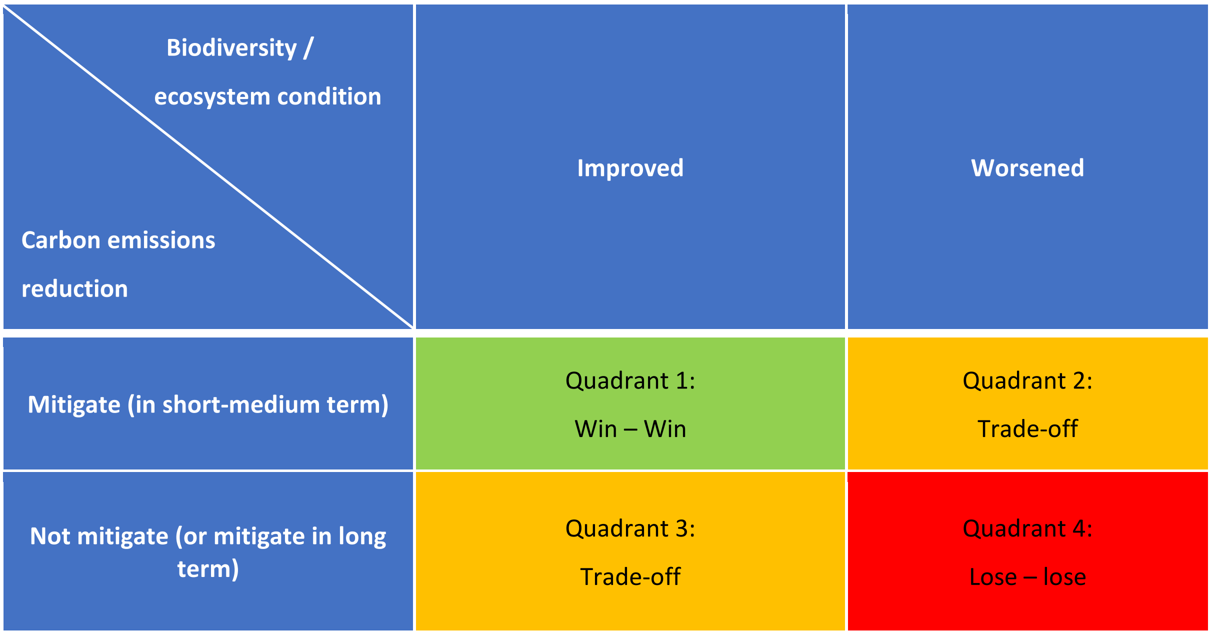
Forest bioenergy pathways which fit within the first quadrant are the ones that are very likely to contribute to climate change mitigation in a short-medium term, and at the same time are likely to improve the condition of local ecosystems and biodiversity (or at least do not affect paths of ecosystem restoration).

Pathways in the fourth quadrant are the ones that are unlikely to contribute to climate change mitigation in the short-medium term and at the same time are likely to further degrade ecosystems' condition.

Conversely, pathways in quadrants 2 and 3 are the ones for which trade-offs between climate mitigation and biodiversity can be identified or assumed. Pathways in quadrant 2 are the ones that even though they are likely to mitigate climate change, they are also likely to negatively impact local biodiversity. For these pathways, safeguards or mitigation strategies should be investigated, and if available, should be considered mandated as contingent to the promotion of bioenergy. This case is also the only case in which the trade-off mentioned above (global climate change mitigation vs. local degradation) could influence the final evaluation of the pathway.

Pathways in the third quadrant are likely to improve local ecosystem condition, but might not mitigate climate change in the short term. In these cases, bioenergy production might be seen as a by-product of restoration operations.

In both cases in quadrants 2 & 3, trade-offs that cannot be resolved will need to be weighted and discussed during the decision-making process.



Biodiversity / ecosystem condition Carbon emissions reduction	Improved	Worsened
Mitigate (in short-medium term)	Quadrant 1: Win – Win	Quadrant 2: Trade-off
Not mitigate (or mitigate in long term)	Quadrant 3: Trade-off	Quadrant 4: Lose – lose

Figure 37. Categories of assessment for forest bioenergy pathways

In view of providing a synthesis from the literature that could be helpful for decision making, we produce a series of bioenergy pathways archetypes[40] which we qualify for their impact on carbon emissions (based on the analysis presented in section 5.6) and for their impacts on biodiversity and ecosystem conditions (based on the literature review in section 5.8).

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[40] Intended as specific pathways that capture the general findings from the literature.

Concerning carbon impacts, based on the results in Table 5, we disaggregate the archetypes into four broad categories, mainly based on carbon-debt payback times. To be noticed that, as explained in section 5.6, since the results of carbon accounting are strongly influenced by the assumptions of the analysis, generalizing is possible only through broad-ranging categories.

The four categories defined for the carbon accounting assessment are the following ones:

- Short-term: these are pathways which are likely to achieve carbon emissions savings compared to fossil sources immediately or within one or two decades.
- Likely medium-term: these are pathways which are likely to achieve carbon emissions savings within three to five decades.
- Unlikely medium-term: these are pathways which are not likely to achieve carbon emissions savings before five decades.
- Long-term: these are pathways which are likely to achieve carbon emissions savings only in a century scale or even never.

Similarly, we define four broad-ranging categories for the qualitative impact assessment of each archetype on biodiversity:

- High risk (red cross): negative effects on biodiversity attributes or ecosystem condition;
- Neutral – Positive (green tick): negligible or positive effects on biodiversity attributes or ecosystem condition;
- Medium/high risk (red cross + orange exclamation): the pathway can potentially have negative impacts on biodiversity or ecosystem condition, but the actual impact depends on other confounding variables (e.g. landscape availability of dead wood, local conditions, conservation strategies, local forest management etc…) and the final impact could be positive or negative depending on them;
- Medium/low risk (green tick and orange exclamation): pathway is likely to cause little or no negative impacts on local biodiversity or ecosystem condition, but specific conditions should be investigated to make sure that is the case.

5.8 Review of impacts on biodiversity

This section presents the results of our literature review; it is divided into two sub-sections each dealing with one separate intervention. Within each sub-section, we look at the potential role of these interventions to fulfil the additional bioenergy demand and we summarise the potential cause-effect chain of the intervention, including the most relevant impacts that will be assessed through the review. We then summarise the main results of the review, and we present a synthesis of the findings of each study. Finally, we synthesise the findings into a qualitative assessment of the impacts of several archetype pathways.

5.8.1 Removal of logging residues: review and synthesis

5.8.1.1 Framing and background: Why is it important for bioenergy & current management practices?

One of the main responses to an increased production of wood from forests for bioenergy is an increased removal of logging residues. The definition of logging residues is important, because different types of dead wood have different ecological roles and, consequently, specific impacts are associated to their removal (or addition). In this section we differentiate among the following type of residues:

- Fine Woody Debris (FWD) (including slash, i.e. tops and branches);

- Coarse Woody Debris (CWD) (including snags, standing dead trees, and high stumps);
- Low-stumps.

While some studies include also small logs without commercial value, for instance harvested during pre-commercial thinning or during cleaning operations, we do not include those as they are not considered 'dead wood'.

We do, however, briefly investigate also the impact of salvage logging (i.e. removing dead wood after different types of natural disturbances).

Stokland et al. (2012) define the term *saproxylic* as "any species that depends, during some part of its life cycle, upon wounded or decaying woody material from living, weakened or dead trees". It is beyond the scope of this chapter to go in-depth into saproxylic ecology, but some notes on the matter are important to understand the potential negative impacts of removing logging residues from forest ecosystems.

A simplified representation of saproxylic food webs contains decomposers, fungi and bacteria, which break woody polymers such as lignin and cellulose through enzymatic digestion to produce organic polymers and monomers, and detritivores species which consume both decaying wood as well as the fungi and bacteria themselves. Detritivores are comprised mainly by saproxylic beetles, midges and flies, termites and mites (Stokland, 2012). Many of these species also complement the decaying function of fungi through additional mechanical disintegration of the decaying wood (Garrick et al., 2019).

Additionally, decaying dead wood has other ecological functions beside acting as a primary source of nutrition; insects, birds, and mammal species use dead or decaying wood for nesting, and epixylic lichens and mosses use dead wood as a substrate for growth.

Additionally, saproxylic species have an essential role in nutrient cycling (mineralization and humification) in forest ecosystems by decomposing and returning nutrients and carbon to the soil, making them available for new growth (Ulyshen, 2016).

Therefore, far from being simple 'residues', dead wood plays an essential role within forest ecology, and a decline in saproxylic species would thus potentially reverberate up the food web (Moose et al., 2019; Stokland, 2012; Ulyshen, 2016).

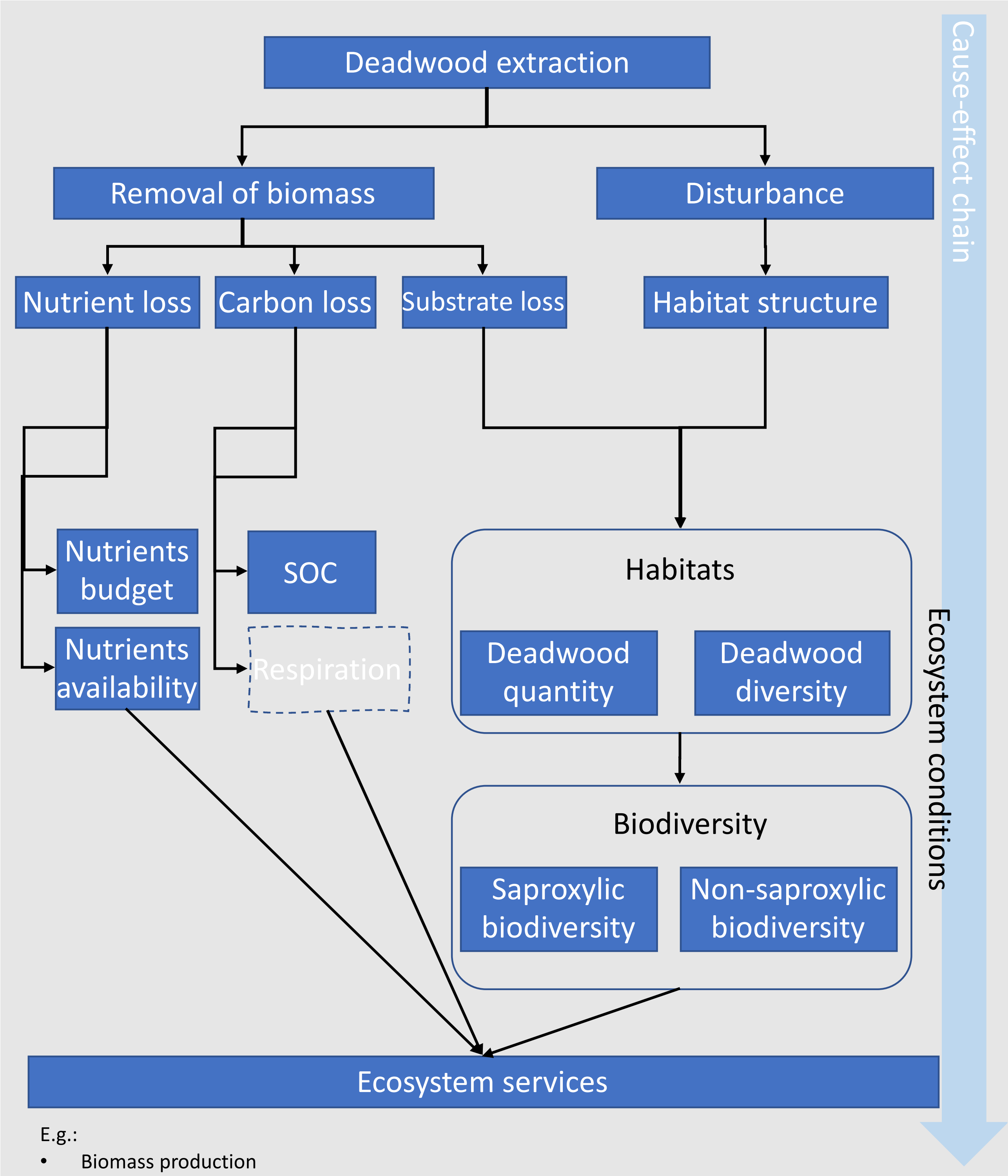
Indeed, currently saproxylic species are a highly threatened taxonomic group, mainly due to the shift towards intensive commercial forestry which has modified forest ecosystems, reducing old and veteran trees, and drastically reducing the amount and diversity of dead wood across managed forests (either through active removal of residues, salvage logging, and through site preparation techniques which are destructive to legacy structures) (Davies et al., 2008; Seibold et al., 2015b). The main endangered species are specialists associated with the later stages of wood decomposition and the decay of veteran trees.

Figure 38 presents a simplified schematic representation of the potential impacts of the removal of logging residues and other dead wood material on ecosystem condition and biodiversity.

1. By removing residues:
    - Nutrients are removed;
        - This can lead to loss of productivity in the long term;
        - However, it might decrease nitrate leaching;
        - And it might remove a source of N-immobilization due to the growth of saproxylic fungi (especially valid for stumps).
    - A carbon source is removed:

        - This could lead to a decrease in Soil Organic Carbon in the long term (with all associated impacts on the forest ecosystem).
        - A source of CO_2 through respiration and decomposition is removed (but this is accounted within the carbon accounting process).
    - Substrates on which all saproxylic species depend on are removed;

2. The operations for logging residues collection and removal may lead to:
    - Extraction or damage to other legacy dead wood with high ecological value (such as older snags/logs or other CWD);
    - Creation of ecological traps when piles of residues are left in the forest and then removed and burned.



E.g.:

- Biomass production
- Climate regulation
- Lifecycle maintenance, habitat, and gene pool protection
- Decomposition and fixing processes
- Existence and bequest
- …

Figure 38. Cause effect chain following the removal of logging residues. Adapted from: (Ranius et al., 2018)

5.8.1.2 Review of impacts on ecosystem condition attributes

Based on the simplified cause-effect chain in Figure 38 and on the relevant attributes for ecosystems' condition and biodiversity assessment defined in Figure 38, we have selected the following impact categories to evaluate the outcomes of logging residues removal found in the literature:

(a) Habitat relevance: this attribute is at a higher level of the cause-effect chain compared to actual impacts on biodiversity attributes, but it is chosen as a relevant proxy for potential impacts of residues removal because the measurements in species changes might be underestimated due to time-lags or other confounding variables (e.g. landscape effects). It is also used to identify the potential impacts on different taxa and species of interest for conservation

(b) Impacts on community composition (e.g. changes in species richness indicators or changes in assemblages) when residues are removed

(c) Impacts on species populations (e.g. species abundance) when residues are removed

(d) Impacts on nutrients budget and availability

(e) Impacts on Soil Organic Carbon

(f) Impacts on productivity of the forest: this attribute is at a lower level in the cause-effect chain so it can be considered a proxy including effects also from nutrients availability and soil physico-chemical quality

As shown in section 5.7.2, the MAES framework defines a large set of ecosystems' condition attributes. Therefore, this should be considered just as a sub-set of all potential impacts. We invite further research expanding the impacts assessed, whenever possible, to produce an even more complete assessment, for instance considering impacts on other attributes of soil quality and quantity (erosion, compaction etc..) as well as impacts on fire or pest frequency.

The impacts are strongly influenced by several factors (Seibold et al., 2015a). The synthesis of literature studies presented below differentiates as much as possible pathways based on these factors (i.e. different IDs are assigned to pathways with different characteristics). The main differentiation is based on eco-climatic conditions, by differentiating by biome and ecosystem type, as well as on size and type of residues considered.

In the extensive literature table, which can be obtained by contacting the authors, comments to each study capture the impacts of the taxonomical group considered, the spatial and temporal scales considered in each study, the species of wood, as well as other abiotic and biotic factors.

5.8.1.3 Review findings: removals of residues

Table 7 and Figure 39 aim to provide a synthesis of the results found in the 18 studies[41]. Below we summarise the main results from the synthesis:

— A general consensus exists that CWD (e.g. snags, logs, high stumps) is ecologically more important than FWD as a habitat for saproxylic species. Many studies indeed focus on the impact of CWD creation within stands to promote saproxylic biodiversity. Vitkova et al. (2018) even states that it is misleading to include slash and low-stumps among the accounting of dead wood quantity indicators as those have very little ecological role (Vítková et al., 2018).

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[41] Please note that since most of the studies reviewed are in turn 'reviews' or 'meta-analysis', our synthesis captures the results of a much larger amount of studies.

- Concerning the importance of various types and characteristics of dead wood on biodiversity, Vítková et al. (2018) present a clear summary of what management of dead wood in productive forests should strive for:
    - Diversity of position and arrangement: sun-exposed vs shaded; standing vs lying dead wood. Fungi and bryophyte are favoured by shaded moist conditions, while dry and warmer conditions are suitable for saproxylic beetles and lichens. Standing dead wood seems to host more saproxylic species, but lying dead wood seems to be better for fungi and bryophytes.
    - Diversity of decay stages: different assemblages can be found on dead wood at different decay stages. Intermediate and advanced decay stages appear to be most favourable for many species of fungi, including many red-listed species. Small vertebrates seek earlier stages of decay for foraging.
    - Diversity of tree species: species with slow decay should be prioritized (oaks>spruce>pines>beech). Broadleaves carry more microhabitats than conifers.
    - Diversity of sizes of dead wood: presence of large dimensions of dead wood (CWD) is more important than the position of dead wood (standing/lying). Larger dimensions also take longer to decay so they contribute to have suitable habitats available for longer time. Large logs cannot be replaced by the same amount of smaller logs. Some smaller size brash is also necessary because some species require smaller stem and branches (the study clearly states that only large dead wood with length >1 m and diameter at smaller end >7 cm can be considered important to support saproxylic species, all other dead wood is not considered sufficient habitat, including small stumps <15 cm diameter and 20-30 cm height are not considered important habitats).
- Other studies, though, disagree with disqualifying the removal of stumps and slash as ecologically non-significant. Additionally, the impacts of low stumps are often differentiated from the impacts of removing slash and FWD.
- Most of the studies identify low stumps as an important habitat. Ranius et al. (2018) state that in boreal and temperate forests, many species, including red-listed ones, have been found in slash and stumps, even though there tend to be more red-listed species in other types of dead wood. Bouget et al. (2012) found that low stumps appear to be richer (for pine) or as species rich as downed large logs (spruce, birch, aspen, pine, spruce, oak), and even as rich as snags (spruce, oak). Hiron et al. (2017) found that in their study in boreal forests in Sweden, 20% of red-listed species were found on stumps. And that more than 50% of the population for 20 rare species was found on stumps.
- There seems to be general consensus that FWD has a lower ecological importance than CWD and low stumps, also because of the relatively quicker decay rate of FWDs, meaning that they can provide habitat only to species adapted to decaying wood in an initial status of decay. Nonetheless, Bouget et al. (2012) found that species composition differs between FWD and larger dead wood pieces and that FWD specialist species exist. Additionally, they state that there is complementarity between species assemblages between different dead wood types, and thus it is impossible to substitute one dead wood category for the other. Other studies agree that deciduous FWD might host more specialist and red-listed species than coniferous residues.
- Concerning the measured impacts of removal of slash and CWD, there is clear consensus that the removal of CWD has a negative impact both on species richness and abundance of saproxylic species. Additionally, Riffell et al. (2011) found a significant decrease in birds' diversity and abundance, supporting the importance of CWD not only for saproxylic species

but also for Excavators guild birds feeding, higher on the trophic web, as well as for cavity nesters which benefit from the structural diversity provided by CWD.

- There appears to be more scarcity of results detailing the impact of FWD and slash removals on biodiversity. Both Ranius et al. (2018) and de Jong et al. (2017) point out that removal of FWD is unlikely to cause any extinction at landscape scale, and that there are thresholds of removals above which negative impacts would start to appear. De Jong et al. (2017) place this threshold at 40% of slash removal across the landscape and 14% of low stumps removal.
- The impacts of removal of low stumps is also usually associated with negative impacts on species diversity and abundance.
- An important issue which arises from the literature is whether impacts should be evaluated differently depending on the conservation status of the species involved. For instance, de Jong & Dahlberg (2017) focused on the potential impacts of residues removals on Species of Conservation Interest (SCI) and red-listed species. Their argument is that the impacts of the intervention should not just be evaluated on direction and magnitude, but it should be evaluated in its ecological significance. Thus, their reasoning is that the goal should not be to cause no negative impact on any species, but rather that the intervention should not cause local extinctions of species, thus the focus on SCI, red-listed species or potential impacts on specialist species.
- Others use a different qualifier to weigh the potential impacts. For instance, Ulyshen (2016) highlights the importance of certain taxa in promoting wood decomposition processes, such as wood-boring beetles and termites, and thus impacts on these functional groups might be ecologically more consequential than general species richness metrics.
- Other authors disagree with focusing on specific taxa or functional groups, and provide reasons for a more ‘precautionary’ approach for which any species decline is considered dangerous and significant. For instance Sverdrup-Tygerson et al. (2014) point out that there may be a time-lag between interventions and impacts and that the well-known ‘extinction debt’ might be triggered even though shorter-term effects appear small. Another counter-point is that one criterion for inclusion into the IUCN Red-list of threatened species is a population decline above 50% in 10 years, meaning that species which are not yet red-listed may become so as an effect of the intervention. Snäll et al. (2017) presents a clear example of this phenomenon: they modelled the influence of different rates of low stumps removal on various metapopulations of epixylic lichens and they found that high rates of stumps removal would cause five out of six species of lichens to be red-listed as their populations would decline by more than 50%.
- Concerning impacts on soil organic matter, Thiffault et al. (2011) found large variability in the impacts of whole-tree-harvest on SOC, with half of the results showing negative impacts and the other half showing improved SOC content. They concluded that residues removal might have a worse impact in soils which are already poor in Carbon, and in boreal stands. However, more recent meta-analyses have come to different conclusions. Achat et al. (2015) found that whole tree harvesting might result in a decrease of up to 10% of SOC stocks compared to stem-only harvest, across all soil layers. Although the authors included in their meta-analysis all types of residues removal (i.e. branches, stumps, foliage or a combination of these items), Achat et al. (2015b) disaggregate the impacts based on the type of residues removed and find that the removal of only branches has limited impact, while the removal of foliage and stumps additional to branches generates the worst declines in SOC. Wan et al. (2018) support these findings, although they find the main difference to be in the first 20 cm of soil profile and they find this effect might be temporary since the difference in SOC seems to decrease with time.

- The same studies have also assessed the potential impact of residues removal on soil nutrients' pools. Both Achat et al. (2015b) and Thiffault et al. (2011) find significant decrease in Nitrogen and Phosphorous concentration and availability following residues removal.
- As shown in Figure 38, impacts on SOC, physical soil properties, nutrients availability, as well as on biodiversity, may affect negatively several ecosystem services. Biomass productivity and tree growth are two straightforward variables that can be monitored to evaluate the combined effect of residues removal. The literature does not seem to point to a consensus on the impacts on forest growth and productivity. Thiffault et al. (2011) found a significant decrease in seedling height when residues were removed, up to 25 years after harvest; they ascribe this especially to the decrease in N availability. Achat et al. (2015b) found similar decrease in tree growth parameters, but mainly for treatments including removal of branches and foliage, while growth was not significantly affected when only branches were removed. Ranius et al. (2018) found that only a third of the studies found a decrease in tree growth when FWD were removed, while two thirds of the studies found no difference. For low stumps removal, a third of the studies actually found increased growth after stumps removal. Finally, Persson & Egnell (2018) substantiate this latter finding, with stumps, or stumps and slash removal having no negative effect on stand growth in trials in Sweden and Finland, in the long term (24-36 years after harvest).
- Finally, as a sub-category of this intervention we have included a recent meta-analysis by Thorn et al. (2018) investigating the impact of salvage logging on several taxa. They find significant negative effects on saproxylic species especially in salvage operations after fires and windthrow disturbances. They state that these disturbances create specific habitats and structures for many species which are removed by salvage operations, which additionally also contribute to the destruction of existing legacy structures. They conclude though, that retention of snags and naturally disturbed elements and landscape planning including salvage-exclusion areas could significantly mitigate the negative impacts of salvage logging. Furthermore, they find positive impacts on taxa with salvage operations after pest outbreaks.

Table 7. Case studies and impact assessment for logging residues removal intervention. Greyed out assessment means further comments are needed to explain the evaluation.

Study	Geographical scope		Intervention details		Impact categories					
					Habitat relevance	**Community composition (saproxylic)**	**Species populations (saproxylic)**	**Nutrients**	**SOC**	**Productivity**
	Biome	**Country**	**Type of dead wood**	**Dead wood characteristics**	**Qualitative assessment**	**Impact assessment**	**Impact assessment**	**Impact assessment**	**Impact assessment**	**Impact assessment**
Koivula, 2020	Boreal / Temperate	SE, NO, FI, EE	CWD		+	↘				
Gustafsson (2020)	Boreal / Temperate	SE, NO, FI, EE, LV, LT, RU	CWD	high stumps	+					
Gustafsson (2020)	Boreal / Temperate	SE, NO, FI, EE, LV, LT, RU	CWD	Sun-exposed	+					
Sandstrom (2019)	Boreal / Temperate	FI, EE, SE, NO, UK, US, CA, EE, AU, DE.	CWD			↘	↘			
Vitkova (2018)	Temperate	Central Europe	CWD		+					
de Jong & Dahlberg (2017)	Boreal / Temperate	Mainly SE	CWD	all	+					
Seibold et al. (2015)	Boreal / Temperate	Global	CWD			↘				
Lassauce et al. (2011)	Boreal / Temperate	Global	CWD	Downed logs		↘				
Lassauce et al. (2011)	Boreal / Temperate	Global	CWD	Standing snags		↘				

Riffell (2011)	Boreal / Temperate	USA / CA	CWD + Low Stumps			→	↘			
Ranius et al. (2018)	Boreal / Temperate	Northern Europe, CA, USA, AU.	Low stumps		+		↘			→ ↗
Bouget et al. (2012)	Boreal / Temperate	Europe	Low stumps		+					
Lassauce et al. (2011)	Boreal	Global	Low stumps			↗				
Lassauce et al. (2011)	Temperate	Global	Low stumps			→				
Hiron et al. (2017)	Boreal	SE	Low stumps	spruce / birch	+					
Persson & Egnell (2018)	Boreal / Temperate	SE, FI, CA	Low stumps		+ / =	↘	↘		→	→
de Jong & Dahlberg (2017)	Boreal / Temperate	Mainly SE	FWD + Low Stumps	coniferous species	-					
de Jong & Dahlberg (2017)	Boreal / Temperate	Mainly SE	FWD + Low Stumps	deciduous species	+					
de Jong (2017b)	Boreal / Temperate	Mainly SE	FWD + Low Stumps			↘ →				
Mayer (2020)	Boreal / Temperate	Global	FWD + Low Stumps						↘	
Vitkova (2018)	Temperate	Central Europe	FWD + Low Stumps		-					
Achat et al. (2015)	Boreal / Temperate / Tropical / Subtropical	Global	FWD / Low Stumps / foliage						↘	
Achat et al. (2015b)	Boreal / Temperate / Tropical / Subtropical	Global	FWD + Low Stumps + foliage					↘	↘	↘

de Jong (2017b)	Boreal / Temperate	Mainly SE	FWD			↘ →				
Bouget et al. (2012)	Boreal / Temperate	Europe	FWD		+ / =					
Thiffault et al. (2011)	Boreal / Temperate	Global	FWD					↘ →	→	↘
Wan et al. (2018)	Boreal / Temperate / Tropical / Subtropical	Global	FWD						↘	
Achat et al. (2015b)	Boreal / Temperate / Tropical / Subtropical	Global	FWD					→	→	→ ↘
Hiron et al. (2017)	Boreal	SE	FWD	birch	+ / =					
Hiron et al. (2017)	Boreal	SE	FWD	spruce	=					
Ranius et al. (2018)	Boreal / Temperate	Northern Europe, CA, USA, AU.	FWD		+		↘			→ ↘
Thorn et al. (2017)	Boreal / Temperate	US, CA, ES, FR, IT, AT, EE, KR, AU	Salvage logging	after wildfires		↘				
Thorn et al. (2017)	Boreal / Temperate	US, CA, ES, FR, IT, AT, EE, KR, AU	Salvage logging	after windstorms		↘				
Thorn et al. (2017)	Boreal / Temperate	US, CA, ES, FR, IT, AT, EE, KR, AU	Salvage logging	after insect outbreaks		→				

5.8.1.4 Synthesis of evidence

As described in detail in section 5.7, based on the findings from the literature review described above, we defined a few pathways archetypes representing the removal of logging residues and we have then, based on the literature review presented in the previous section, assigned a qualifier to their impact on biodiversity. The pathways archetypes with their qualitative assessment are captured in Figure 39.

For clarity, we repeat here the categories for the qualitative impact assessment of each archetype on biodiversity:

- High risk (red cross): negative effects on biodiversity attributes or ecosystem condition;
- Neutral – Positive (green tick): negligible or positive effects on biodiversity attributes or ecosystem condition;
- Medium/high risk (red cross + orange exclamation): the pathway can potentially have negative impacts on biodiversity or ecosystem condition, but the actual impact depends on other confounding variables (e.g. landscape availability of dead wood, local conditions, conservation strategies, local forest management etc…) and the final impact could be positive or negative depending on them;
- Medium/low risk (green tick and orange exclamation): pathway is likely to cause little or no negative impacts on local biodiversity or ecosystem condition, but specific conditions should be investigated to make sure that is the case.

The four categories and the archetypes should be seen as simplifications, depicting a synthetic picture of the whole body of evidence and do not aim to capture all the nuisances described above. However, we reckon the synthesis provides important information which can then be analysed together with information on carbon impacts to draw conclusions on potential trade-offs (see section 5.9). Additionally, these archetypes can be considered to be an initial basis for discussion, while further disaggregation, refinement, and details can be added in the future to improve or add new archetypes. To be noticed also that the qualifiers in Figure 39 represent the theoretical risk associated with the pathways, while the actual risk of these pathways taking place should be evaluated based on existing local legislations and guidelines, as well as on the actual implementation and enforcement of such regulatory or voluntary principles. Due to the general nature of the assessment, for the pathways where this is applicable, we recall the potential safeguards contained within general principles and standards of Sustainable Forest Management and related certification schemes (Forest Stewardship Council, 2015; Programme for the Endorsement of Forest Certification, 2018). Pathways with notable safeguards in certification standards or forestry recommendations are noted with an asterisk in Figure 39.

The results in Figure 39 can be summarised in the following points:

1. Coarse woody debris, such as snags, high stumps, and downed logs have the greatest ecological role for saproxylic species. Pathway nr.1 therefore clearly places high risk on forest ecosystems. PEFC standards explicitly recommend that standing and fallen dead wood shall be left in quantities and distribution necessary to safeguard biological diversity. However, Johansson et al. (2013), Jonsson et al. (2016) and Kuuluvainen et al. (2019), found that the translation of this principle in practical guidelines was insufficient, in quantity and quality, compared to what would be needed to maintain healthy ecosystems.
2. De Jong & Dahlberg (2017) and de Jong et al. (2017) and others, all highlight the importance of implementing retention (or removal) thresholds also for FWD and low stumps. Based on ecological modelling and conditions in Sweden, they suggest that harvesting 50% of slash and 10-20% of stumps in spruce-dominated landscapes might

have limited to negligible impact on biodiversity in general and a marked effect on only a few species. It should be pointed out that Thiffault et al. (2015) reviewed the removal rates of harvest residues (mainly slash, stumps are excluded) in boreal and temperate forest trials and found an average rate of 50% being removed, with an average in Finland and Sweden of 76%. Voluntary certification standards do not explicitly mention slash or low stumps retention, however local recommendations and guidelines for forest management may address this. For instance, Nilsson et al. (2018) reports the recommendations of the Swedish Forest Agency to retain at least 20% of the FWD (tops and slash) at clear cut sites. Fritts et al. (2016) reports similar guidelines in US. It is clear from the literature that total removal of FWD and, even worse, of low stumps would be detrimental to the ecosystem, that is why all pathways are qualified as 'high risk' when removal is above the threshold.

3. A large fraction of the dead wood amount present in intensively managed clear- cut stands is in many cases composed mainly of slash and low-stumps, which might therefore constitute an important habitat for several species. However, it is understood that dead wood management should be tackled on a landscape scale (Mason and Zapponi, 2016), and that retention strategies can be implemented to improve ecosystem condition for saproxylic species, e.g. through increased retention of CWD and creation of structures such as high stumps, which would be more ecologically relevant than FWD. Indeed, this is the conclusion reached by de Jong et al. (2017), stating that it might make more sense from a conservation point of view, to increase the amount of different dead wood structures (i.e. high stumps, CWD) rather than restricting the removal of low-stumps, and even less effective, the removal of slash. As highlighted in section 5.8.1, Bouget et al. (2012), however, warn against the complementarity of different dead wood types as habitats. Based on these reflections and the points below, we qualify pathways 3, 5, and 7 as medium-low or low risk.
4. De Jong et al. (2017) state that harvesting of slash and stumps of deciduous species in coniferous landscapes should be avoided, and that harvesting of slash and stumps in deciduous landscapes should be avoided or restricted. These recommendations are reflected in pathways nr. 6 and 7, where pathway 7 is assigned a medium-low risk because of the relatively higher importance of deciduous slash.
5. Pathways 2 and 3 reflect the potential danger of removing foliage and needle on nutrients and tree growth as highlighted by Achat et al. (2015b). Forest management recommendations also advise leaving residues on site for a certain period before collection, in order to dry and shed needles and leaves. However, Nilsson et al. (2018), in an experiment in Sweden, found that a similar fraction of needles is removed whether the residues are left stacked on clear cut site for a whole summer or they are transported directly to the roadside. They conclude that the retention threshold plays a bigger role in maintaining nutrients than de-needling operations. Similarly, recommendations may exist for the compensation of nutrients through ash recycling, depending on local site conditions and residues removal levels. This confirms the high risk evaluated for all pathways where removal is above a locally defined threshold. Additionally, pathway 3 is assigned a medium-low risk because nutrient compensation might be needed at certain sites.
6. Pathways 8 and 9 reflect the lack of consensus and the importance of local specificities in the assessment of the impacts of low stumps removal. While most studies agree on the need for a maximum threshold of removal rate, there does not seem to be a consensus on the actual ecological relevance of low stumps. Indeed, Persson & Egnell (2018) point out that even though low-stumps constitute the main components of dead wood in managed stands in Sweden, and are thus an important habitat for many

generalist saproxylic species, their removal would not cause extinction risks even for specialist species when removal is limited at 10% of the total clear-cut area. As highlighted in section 5.8.1, other studies disagree with focusing only on rare and red-listed species. It is likely that locally defined guidelines and recommendations exist to regulate the removal of stumps, as for instance reported for Sweden by Persson and Egnell (2018). Our assessment is that removal of stumps above locally defined thresholds would pose high risk on ecosystem, while the removal of stumps below threshold could still pose medium-high risk and should be carefully examined on a case by case basis.

7. Additionally, several studies warn that harvesting guidelines and training for the removal of logging residues should be in place to minimize damage on other retention structures (e.g. high-stumps and downed dead logs). SFM certification standards tackle this potential damage; for instance PEFC standards state that 'tending and harvesting operations shall be conducted in a way that does not cause lasting damage to ecosystems. Wherever possible, practical measures shall be taken to maintain or improve biological diversity' (Programme for the Endorsement of Forest Certification, 2018).
8. According to the framework of Forest Management Approaches defined by Duncker et al. (2012), all of these pathways apply to silvicultural managements of medium to high intensity. Low intensity, Close-to-Nature forestry, instead would rely on stem-only harvest.

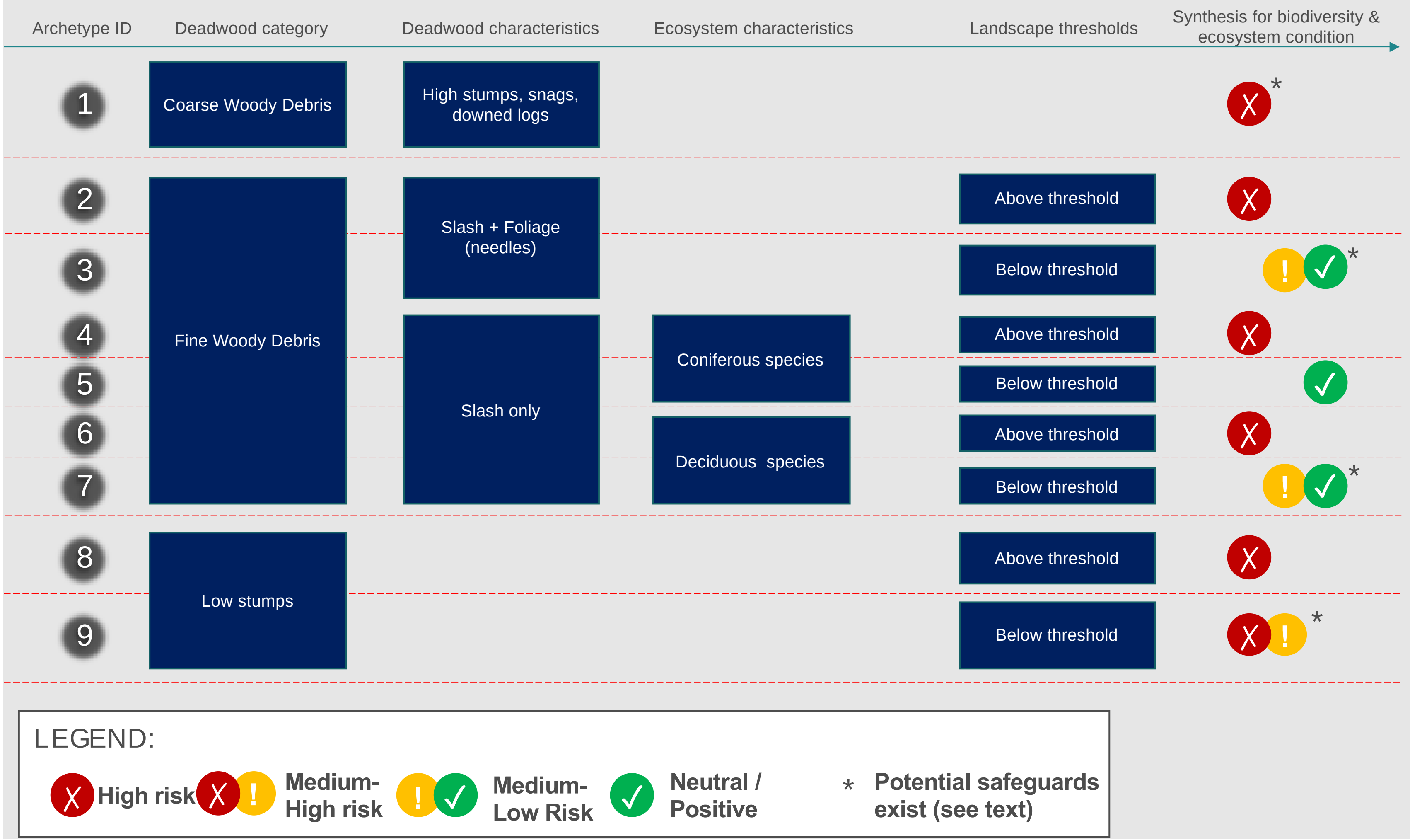

Figure 39. Archetype pathways which represent a synthesis of evidence described in section 5.8.1.3. The risk qualifiers refer to potential risk, that is, unmitigated by existing legislation, recommendations, or voluntary certification schemes. Pathways with an asterisk refer to potential safeguards which are described in the text in section 5.8.1.3.

5.8.2 Afforestation and conversion to plantations: review and synthesis

When talking about forest expansion, the literature presents a wealth of different terminology each with its own nuanced meaning usually reflecting the main goal of the activity under analysis. Some examples of the terms used are: forest landscape restoration, tree planting, afforestation, reforestation, habitat regeneration, rewilding, etc.

In this report we follow the definitions provided by FAO (2020). It is especially important to clarify the distinction between afforestation and reforestation within FAO definitions and the concepts as defined in the broader literature on restoration ecology. In the latter, it is often understood that a*fforestation* represents the planting of trees where they did not historically occur (even though climatic conditions might support forest ecosystems), while the term *reforestation* represents the planting of trees (or other activities favouring natural regeneration) in areas that were deforested in modern times. By following FAO's definitions, in this section, on the other hand, we categorise afforestation as the deliberate planting or seeding of trees on non-forested land, irrespectively of historic land use.

5.8.2.1 Framing and background: why is it important for bioenergy & current management practices?

Griscom et al., (2017) examined how nature could contribute to climate change mitigation. They presented a comprehensive analysis of what they termed "natural climate solutions" (NCS) (also referred to as nature-based solutions): 20 actions for conservation, restoration, and/or improved land management that would increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural ecosystems. Afforestation and tree planting operations are important components of NCS, and are considered to be able to mitigate climate change by increasing the C-stock in the biosphere and producing wood for materials and energy, while at the same time restoring habitats and thus improving ecosystems' condition.

This narrative is omnipresent, from biodiversity policies and strategies (EU, 2020), to climate change mitigation modelling (Harper et al., 2018), and certainly in bioenergy literature (Giuntoli et al., 2020b). However, recent publications have shown that tree planting should not be seen as innately good, but rather should be subjected to similar deep scrutiny applied to other land use changes (Holl and Brancalion, 2020; Lewis et al., 2019).

Additionally, the expansion of intensively managed tree plantations might be taking place not only on currently non-forested land, but rather at the expenses of forests with high environmental value such as naturally regenerating and native forest ecosystems, or even primary and old-growth forests. There is the risk of significantly negative impacts on biodiversity and ecosystems associated with this transition[42]. This conversion can take place directly when harvested natural forests are replanted with dense stands of a single highly productive species: an example of this is the replacement of natural forest ecosystems with highly productive pine plantations in the US South (Baker and Hunter, 2002), as well as Eucalyptus plantations in NW Spain (Calviño-Cancela et al., 2012; Goded et al., 2019). Alternatively, this change could take place indirectly as a result of market-mediated forces: for instance, when unprofitable agricultural land is abandoned and afforested with tree plantations, while other areas of native forest are deforested to create new agricultural land. Hua et al. (2018) present an instructive example from China's afforestation experience: when afforestation is driven simply by market drivers, such as an increase in bioenergy demand could create, without conditional requirements, then productivity becomes the main goal for the new forest land, leading often to monoculture plantations established in low-productivity cropland, but at the same time, if the existing

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[42] Pawson et al. (2013) (Pawson et al., 2013), pag. 1205: "In a world where there are large areas of degraded (formerly forested) land suitable for reforestation, those plantations that replace natural forests rightly deserve criticism".

demand for agricultural products does not decrease, then part (or all) of the afforested cropland might be regained through deforestation of native forest somewhere else. Similarly, Heilmayr et al. (2020) found that afforestation subsidies in Chile resulted in a net growth of plantations at the direct or indirect expenses of native forests, leading to a net decrease in C-stocks and biodiversity. Thus, in a well-known mechanism which has already led to the capping of consumption of food and feed-based biofuels, as well as to the Commission proposal on the Taxonomy Delegated Act excluding food-based biofuels and industrial feedstock from the voluntary system of sustainable financing for climate change mitigation and adaptation, also afforestation operations might drive indirect land use change where native forest is indirectly replaced by monoculture plantations.

Based on these potential mechanisms, this section aims to investigate the potential impacts of afforestation and conversion to plantations on local biodiversity.

5.8.2.2 Review of impacts on ecosystem condition attributes

The overall impacts of afforestation and conversion interventions on ecosystem conditions and biodiversity, depend mainly on the following parameters, depicted in Figure 40:

— historic land use and native ecosystem type;

— land use transition (i.e. previous land use);

— establishment method (i.e. natural regeneration vs. planting or seeding);

— features of planted forest (i.e. species type, species mixture, planting density, size of plantation, landscape mosaic);

— post-planting management objectives (i.e. site preparation, site tending, harvest method);

— potential indirect effects linked with the land use change

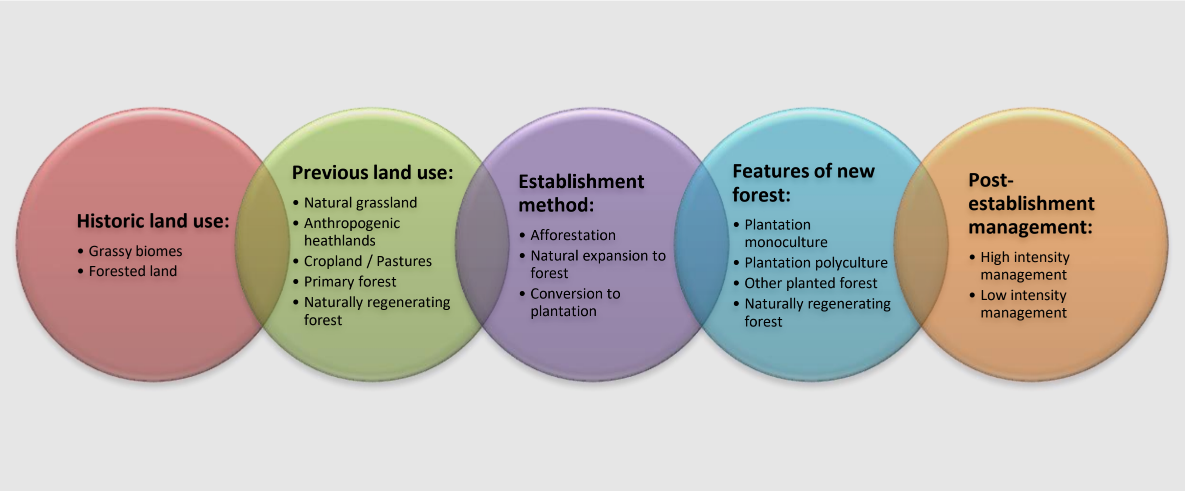

Figure 40. Factors influencing the impact of land use or land occupation change.

The potential impacts of land use and land occupation change on local biodiversity and ecosystems' condition are numerous. For instance, MacKay et al. (2014) and Demarais et al. (2017) stress how the ecological value of tree plantations compared to natural forests is often low due to several factors, such as:

— paucity of habitat components associated with tree senescence, such as dead wood and mature trees

- limited structural complexity both in canopy (even-aged, monoculture) and in understory vegetation (sparse, often actively removed).

From the literature reviewed we can synthesise that the main impact categories of relevance for this report are the following:

- impact on community composition;
- impact on species populations;
- impact on carbon stocks;
- impacts on water cycle (for afforestation);
- impact on soil quality (for conversion to plantations).

5.8.2.3 Review findings: Afforestation

Table 8[43] captures a list of more than 30 case studies measuring the impacts of afforestation on any of the four impact categories mentioned above. Below we summarise the main results from the literature review:

- Although not extensively captured in the case studies, there is clear consensus in the literature that afforestation of primary, ancient grassland ecosystems which were never forests, may have very detrimental effects on local biodiversity; some authors compare these effects to the destructive effects of deforestation (Abreu et al., 2017; Bond, 2016; Bond et al., 2019; Feurdean et al., 2018; Veldman et al., 2015a, 2015b).
- Semi-natural grasslands and anthropogenic heathlands are ecosystems where closed-canopy forest did not historically develop because of natural processes such as fire or mega fauna, or because of extensive management by local people. Local biodiversity adapted to open spaces has evolved in those ecosystems, and afforestation or tree planting of closed-canopy forests is considered as a significant threat for local biodiversity, as highlighted by IPBES (2018a, b). Bubová et al. (2015) reviewed how abandonment of traditional grassland management followed by natural forest succession or active afforestation, is the main driver for the decline of butterfly diversity in Europe.
- The overall carbon impact of afforestation operations needs to be properly calculated including changes in biogenic C-stocks and sinks, the substitution benefits of the newly produced wood, and eventual market-mediated indirect land use change effects. Generally, the overall carbon impact of afforestation is found to be positive, albeit the time scale required might be long (Agostini et al., 2014; Giuntoli et al., 2020b). Nonetheless, not always newly planted forests show a higher C-stock than existing ecosystems, especially when considering the carbon in soil organic matter. Several studies in our review have tried to provide insights. Bárcena et al. (2014) found increased SOC with afforestation on former cropland and heathland in Northern Europe, however afforestation on former grassland actually decreased SOC levels even for mature forests (>30 years). Laganière et al. (2010) found very similar results from their global meta-analysis, with afforestation on former cropland leading to a significant increase in SOC, but no significant changes in SOC for former pastures and natural grasslands. Furthermore, they also found that the tree species (and thus plantation features) influence the final result, with broadleaves forests generating the highest SOC increase and coniferous forests having the same SOC as the former land use. Li et al. (2012), similarly, found increased SOC for new forests on former cropland and pastureland, but a stable or slightly decreased SOC in former grassland.

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[43] [to be included in final version, under preparation]

- The total impact on climate change is not determined only by the carbon balance, but also changes in biogeophysical parameters, such as surface albedo and evapotranspiration, have a major influence on the overall energy balance of the planet (Baldocchi and Penuelas, 2019; EU, 2016b). While this is beyond the scope of this report, it is important to note that new forests will certainly affect the land albedo as well as the water cycle, and the net effect of all these changes should be properly accounted to evaluate the overall impact of afforestation as a climate change mitigation strategy.
- Impacts of afforestation on the water cycle should be carefully considered, even though evidence is still unclear. For instance, Cao et al. (2011) describe the paradoxical situation for which afforestation was promoted to halt desertification in arid and semi-arid regions of China; however, the unintended consequence of this effort was that the newly growing trees had to rely on deep soil water to survive, thus lowering the water table and causing other vegetation to die and furthering the water scarcity of the area. Similar findings were reported by Filoso et al. (2017) who found negative impacts on water yields for afforestation operations for all studies in all locations within their meta-analysis. Albeit they stress that the studies were all short-term and the water yield might stabilise in the longer term. Dye & Versfeld (2007) found that plantations of Eucalyptus established on natural grassland in South Africa were responsible for significantly higher evapotranspiration compared to the native grassland, leading to a reduction of streamflow. Cordero-Rivera et al. (2017) found that Eucalyptus plantations in Spain would cause significant water withdrawal from local streams as opposed to native forests.
- Literature also shows that plantations can be associated with high risk of forest fires and with lower resistance to pests. García-Gonzalo et al. (2012) confirmed previous literature showing that eucalypt stands present the highest fire proneness followed by softwoods (i.e. pine species). However, this was contested by Fernandes et al. (2019) that did not find significant correlations between eucalypt afforestation in Portugal and fires. They however alerted about the risks of undermanaged and abandoned blue gum plantations, especially after large-fire seasons. Cunningham et al. (2005) compared the insect fauna of *Eucalyptus globulus* plantations with native *Eucalyptus marginata* dominated remnant woodland in South-Western Australia, showing that some of the dominant insect species in plantations were known forestry pests.

Concerning the impacts on biodiversity, we group the results from the literature into two main cases: 1) afforestation with intensively managed monoculture plantations; 2) Afforestation with mixed species (polycultures), native species, and low intensity management.

1) Afforestation with intensively managed monoculture plantations

- Looking at impacts on biodiversity, Brockerhoff et al. (2008) state that afforestation would have positive impacts on local biodiversity compared to intensively managed agricultural cropland, regardless of plantation features (e.g. monoculture or polyculture). However, plantation features and post-planting management have an important role to play. Indeed, Hua at el. (2016) and Wang et al. (2019) found that new forests in China, established on impoverished cropland, employing intensively managed monocultures of Eucalyptus, bamboo or Japanese cedar, resulted to have lower species richness of arthropods and bees, and similar richness and abundance for birds. Similarly, Calviño-Cancela et al. (2012) found that eucalyptus plantations in NW Spain had lower understory vegetation diversity than native shrubland developed as first succession after cropland abandonment.
- Several studies, including MacKay et al. (2014), Brockerhoff et al. (2008), and Paquette & Messier (2010) highlight that monoculture plantations might benefit landscape-level biodiversity by:
  - supplementing or complementing resources available in nearby habitats;

    - facilitating dispersal by creating corridors and connecting patches of remnant vegetation;
    - creating buffer zones around habitat fragments thus reducing negative edge effects.
- Fast-growing species such as trees from the genera *Pinus* and *Eucalyptus* are commonly used for afforestation operations, setting up intensively managed monoculture plantations. However, Lindenmayer et al. (2012) strongly warn that these species may be invasive when used outside their original range, and thus care should be placed before planting them. For instance, Calviño-Cancela and Rubido-Bará (2013) analysed the invasive character of *Eucalyptus globulus* in the most common types of surrounding habitats in North-West Spain and suggested removing all new eucalyptus recruits within a radius of 15m from the plantation.

2) Afforestation with mixed species (polycultures), native species, and low intensity management

- The studies of Hua et al. (2016) and Wang et al. (2019) show that mixed plantations of a few species (2 to 5 species) can provide better habitats for local biodiversity. Indeed, Wang et al. (2019) found that arthropod diversity was significantly higher in mixed plantations compared to monocultures and higher than the cropland they substituted. Similarly, Hua et al. (2016) found that bird richness increased when planting mixed species on cropland. When looking into changes in species richness of plants (as a proxy for biodiversity of all taxa), Bremer & Farley (2010) found that replacing secondary forest (intended as naturally regenerating forest on abandoned non-forested land) with plantations of exotic species actually lead to a decrease in species richness, while afforestation with native species lead to an increase in overall species richness. Felton et al. (2016) specifically investigated the impact of replacing monocultures of spruce with mixed-species stands of spruce and birch or spruce and Scots pine in Sweden, and concluded that species richness and abundance of several species would improve.
- Even when conservation of biodiversity might be a primary management goal of afforestation interventions (which is unlikely to be promoted solely by market forces linked to bioenergy demand as intensively managed plantations are far more likely to be promoted (Freer-Smith et al., 2019), there might still be a long time-lag (in the order of centuries) for secondary forests to reach biodiversity levels of native, natural forests, as shown by Curran et al. (2014).
- Similarly to monocultures, polycultures could play an important role in optimizing landscape mosaic diversity, e.g. by placing new forests in proximity with mature, remnant native forests (Gomez-Gonzalez et al., 2020; Hall et al., 2012).

Table 8. Case studies and impact assessment for afforestation intervention. Greyed out assessment means further comments are needed to explain the evaluation. n.a.: not available.

Study	Geographical scope	Intervention details			Impact categories			
					Community composition	**Species populations**	**Carbon Stock**	**Water cycle**
	Country	**Previous land use / comparator**	**Reforestation details**	**Comments**	**Impact assessment**	**Impact assessment**	**Impact assessment**	**Impact assessment**
Hall, 2012	Costa Rica	Cropland + pastures	Regeneration of natural forest	Landscape – scale analysis. Main trend: Natural forest increase	↗		↗	
Hall, 2012	Vietnam	Slash and burn cropland	Abandonment & natural regeneration	Landscape – scale analysis. Main trend: Natural forest increase	↗		↗	
Hua, 2016	China	Cropland	Plantations monocultures (Eucalyptus, bamboo, Japanese cedar)	Eucalyptus: exotic, intensive, 7 years rotation. Bamboo: native, medium/high intensity, selective harvest 1/2 years. Cedar: native, medium intensity, 18/20 years rotation.	→ ↘	→ ↘		
Hua, 2016	China	Cropland	Mixed forest (2 - 5 tree species)	Alder, Japanese cedar, bamboo, toona, happy tree: native, managed as plots of monocultures	↗ ↘	→ ↘		
Wang, 2019	China	Cropland	Plantations monocultures (Eucalyptus, bamboo, Japanese cedar)	Eucalyptus: exotic, intensive, 7 years rotation. Bamboo: native, medium/high intensity, selective harvest 1/2 years. Cedar: native, medium intensity, 18/20 years rotation.	↘			
Wang, 2019	China	Cropland	Mixed forest (2 - 5 tree species)	Alder, Japanese cedar, bamboo, toona, happy tree: native, managed as plots of monocultures	→			
Brockerhoff, 2008	Brazil	Cropland	Plantations of Pine species, Eucalyptus, Araucaria	Exotic	↗			
Bacena, 2014	Denmark, Lithuania,	Cropland	Forests	n.a.			↗	

	Sweden, Finland						
Laganiere (2010)	US, IT, Ethiopia, CA, DK, China	Cropland	Forests	Eucalyptus, Broadleaves mix, Pine, Other coniferous			↗
Li (2012)	Global	Cropland	Forests	Eucalyptus, Broadleaves mix, Pine, Other coniferous			↗
Brockerhoff, 2008	UK	Pastures	Plantations of Pinus, Picea, Larix	Exotic	↗		
Brockerhoff, 2008	New Zealand	Pasture / degraded land	Plantations of Radiata Pine	Exotic. Rotations of about 27 years	↗		
Hoogmoed (2012)	Australia	Pastures	Forests	multiple studies including: native single species plantations, native mixed species, exotic single species.			→
Laganiere (2010)	New Zealand, Australia, Canada, Iceland	Pasture	Forests	Eucalyptus, Broadleaves mix, Pine, Other coniferous			→
Li (2012)	Global	Pasture	Forests	Eucalyptus, Broadleaves mix, Pine, Other coniferous			↗
Felton (2010)	Global	Pasture (without remnant vegetation)	Plantation	Study focuses on 5 taxa: birds, plants, mammals, reptiles/amphibians, invertebrates. The meta-analysis finds significantly different results when the comparator(pastureland) is disaggregated in including or not remnant trees/vegetation. No clear details of plantations or pasture management.	↗	↗	
Felton (2010)	Global	Pasture (without remnant vegetation)	Plantation	Study focuses on 5 taxa: birds, plants, mammals, reptiles/amphibians, invertebrates. The meta-analysis finds significantly different results when the comparator(pastureland) is	→	→	

				disaggregated in including or not remnant trees/vegetation. No clear details of plantations or pasture management.			
Felton (2010)	Global	Pasture (with remnant vegetation)	Plantation	Study focuses on 5 taxa: birds, plants, mammals, reptiles/amphibians, invertebrates. The meta-analysis finds significantly different results when the comparator(pastureland) is disaggregated in including or not remnant trees/vegetation. No clear details of plantations or pasture management.	↘		
Felton (2010)	Global	Pasture (with remnant vegetation)	Plantation	Study focuses on 5 taxa: birds, plants, mammals, reptiles/amphibians, invertebrates. The meta-analysis finds significantly different results when the comparator(pastureland) is disaggregated in including or not remnant trees/vegetation. No clear details of plantations or pasture management.	→	→	
Bremer (2010)	Global	Exotic or Degraded Pasture	Plantation		↗		
Bremer (2010)	Global	Shrubland	Plantation	Afforestation	↘		
Calviño-Cancela et al. (2012)	Spain	Shrubland	Plantation	*Eucalyptus globulus*	↘		
Hall, 2012	Ecuador	Grassland	Pine plantations	Main trend at landscape level: natural grassland to plantation	↘		↘
Bacena, 2014	Ireland	Grassland	Forests	n.a.			↘
Laganiere (2010)	New Zealand, US, UK, Brazil, Germany, Ecuador	Grassland	Forests	Eucalyptus, Broadleaves mix, Pine, Other coniferous			→

Li (2012)	Global	Grassland	Forests	Eucalyptus, Broadleaves mix, Pine, Other coniferous		→	
Dye (2007)	South Africa	Grassland	Plantations				↘
Bremer (2010)	Global	Grassland	Plantation	Afforestation of natural grassland	↘		
Bacena, 2014	Iceland	Heathland	Forests	n.a.		↗	
Felton (2016)	Sweden	Monoculture plantation (>90% Norway Spruce)	Mixed - tree plantation	Spruce - Birch mixture (Birch naturally regenerated)	↗		
Felton (2016)	Sweden	Monoculture plantation (>90% Norway Spruce)	Mixed - tree plantation	Spruce - Scots Pine (Pine naturally regenerated)	↗		
Bremer (2010)	Global	Secondary forest	Plantation (Native species)	Secondary forest = naturally regenerating forest on abandoned land previously not forest.	↗		
Bremer (2010)	Global	Secondary forest	Plantation (Exotic species)	Secondary forest = naturally regenerating forest on abandoned land previously not forest.	↘		

5.8.2.4 *Review findings: Conversion to plantation*

Table 8 presents a list of case studies collected from the literature studying the impacts of conversion of natural or primary forests into plantations.

- There is general consensus across the literature that substituting native, naturally regenerating forests with intensively managed plantations has negative consequences for local biodiversity across regions and taxa assessed. This is substantiated by the case studies analysed as well as by several reviews on the role of plantations for biodiversity conservation and climate change mitigation (Brockerhoff et al., 2013, 2008; Paquette and Messier, 2010; Pawson et al., 2013).
- Firstly, there is clear consensus on the negative impact of substituting primary, old-growth forest with limited or absent management, with plantations, as shown by the results presented by Bremer et al. (2010) and Chaudhary et al. (2016). Numerous species are strictly limited to natural old growth forests and are lost when these are transformed into plantations (Eckelt et al., 2018).
- A recent meta-analysis by Castaño-Villa et al. (2019) has highlighted how replacing native forests with plantations has a negative impact both on species richness and on population abundances of birds. They found that plantations employing exotic species impacted more negatively biodiversity than plantations with native species. They explain that, contrary to exotic species, the shared evolutionary history between plantations of native species and natural forest favours local, endemic biodiversity. Further, they found that mixed species plantations showed less negative impacts than monocultures, since more structural complexity favours bird biodiversity. Finally, they found that plantations established with mixed native species and managed for conservation purposes (e.g. long rotation times and connected to remnant native patches) could have a neutral or even positive impacts for birds richness and abundance. These findings are supported also by specific case studies and for different taxa, such as reported in Calviño-Cancela et al. (2012), Fierro et al. (2017), Goded et al. (2019), Hua et al. (2016) and Wang et al. (2019).
- MacKay et al. (2014) showed that even mature plantations (40-50 years old spruce plantations in Canada) are not able to provide suitable habitat for bird species adapted to mature, and old-growth forests. Haskell et al. (2006) supported this conclusion, finding that loblolly pine plantations in south-eastern USA presented an impoverished diversity of bird species compared to native oak-hickory forests for any age of the plantation. They even found that pine plantations were impoverished as compared to exurban areas with human occupation. They concluded that definitions which conflate plantations with natural forests provide a distorted image of the ecological role of plantations which seriously risks misleading conservation policies.
- Indirect, market-mediated effects are almost always present when changing the use of a scarce resource such as land. Thus, afforestation operations should be treated like any other land use change and second and third order effects should be investigated carefully (Hua et al., 2018).
- Other indirect effects might have to do with land sparing vs. land sharing strategies. Paquette & Messier (2010) make the case that an increase in high-productivity plantations might create the conditions to decrease intensity in other forested areas and expand areas of full protection.
- According to the findings from the global meta-analysis by Liao et al. (2010), total ecosystem C stocks were 28% lower in plantations compared to natural forests. This result was consistent across all carbon pools, regardless of plantation age or tree species planted. This is consistent with the carbon accounting study by Sterman et al. (2018) which found

that replacing oak-hickory forests with loblolly pine plantations for bioenergy in the US southeast would not generate climate change mitigation before 60-70 years (when considering coal substitution) or even >120 years when considering natural gas substitution. Similarly, Lewis et al. (2019) make the case that restoring natural forests might lead to much higher carbon sequestration than plantations.

- Finally, another global meta-analysis by Liao et al. (2012) found that plantations show significantly degraded parameters for soil quality compared to natural forests, including lower soil bulk density, and soil C and N concentration. Thus, they conclude that plantations do not have the same function of maintaining soil fertility as compared to natural forests.

Table 9. Case studies and impact assessment for ‘conversion to plantation’ intervention. Greyed out assessment means further comments are needed to explain the evaluation.

Study	Geographical scope		Intervention details			Impact categories			
						Community composition	**Species populations**	**Carbon Stock**	**Soil quality**
	Country	**Predominant native ecosystem**	**Natural comparator**	**Plantation type**	**Comments**	**Impact assessment**	**Impact assessment**	**Impact assessment**	**Impact assessment**
Hua, 2016	China	Broadleaf, subtropical evergreen	Native forest	Plantations monocultures (Eucalyptus, bamboo, Japanese cedar)	Eucalyptus: exotic, intensive, 7 years rotation. Bamboo: native, medium/high intenstity, selective harvest 1/2 years. Cedar: native, medium intensity, 18/20 years rotation.	↘	↘		
Hua, 2016	China	Broadleaf, subtropical evergreen	Native forest	Mixed forest (2 - 5 tree species)	Alder, Japanese cedar, baomboo, toona, happy tree: native, managed as plots of monocultures	↘	↘		
Wang, 2019	China	Broadleaf, subtropical evergreen	Native forest	Plantations monocultures (Eucalyptus, bamboo, Japanese cedar)	Eucalyptus: exotic, intensive, 7 years rotation. Bamboo: native, medium/high intenstity, selective harvest 1/2 years. Cedar: native, medium intensity, 18/20 years rotation.	↘			
Wang, 2019	China	Broadleaf, subtropical evergreen	Native forest	Mixed forest (2 - 5 tree species)	Alder, Japanese cedar, baomboo, toona, happy tree: native, managed as plots of monocultures	→			
Fierro (2017)	Chile	Maulino forest: deciduous species dominated by *Nothofagus glauca*	Native forest	Monterrey Pine (*Pinus radiata)*	The study focuses on saproxylic beetles and quantity of available deadwood as a proxy for saproxylic habitats.	→ ↘			

Fierro (2017)	Chile	Maulino forest: deciduous species dominated by *Nothofagus glauca*	Native forest	Eucalyptus (*Eucalyptus globulus)*	The study focuses on saproxylic beetles and quantity of available deadwood as a proxy for saproxylic habitats.	↘			
Castano-Villa (2019)	Global		Native forest	All	Excludes oil palm, coffee, cocoa, banana, hybrid poplar plantations	↘	↘		
Castano-Villa (2019)	Global		Native forest	All	Native species	↘	→		
Castano-Villa (2019)	Global		Native forest	All	Exotic species	↘	↘		
Castano-Villa (2019)	Global		Native forest	All	Mixed species	→	→		
Castano-Villa (2019)	Global		Native forest	All	Monocultures	↘	↘		
Castano-Villa (2019)	Global		Native forest	All	Tropical regions	↘	↘		
Castano-Villa (2019)	Global		Native forest	All	Temperate regions	↘	↘		
Castano-Villa (2019)	Global		Native forest	All	Protective plantations	→	↗		
Castano-Villa (2019)	Global		Native forest	All	Commercial plantations	↘	↘		
Liao, 2012	Global		Native forest	All					↘
Liao, 2010	Global		Native forest	All				↘	
MacKay (2014)	Canada	Native coniferous species: red, white, black spruce, balsam fir	Native forest	Plantation	Mature plantations (40 - 50 years), mainly white and black spruce. Pre-commercial,	↘			

					commercial thinning, post-planting herbicide application			
Haskell (2006)	United States	Native forests are mainly composed of hardwood species. In the case studied, the forest is composed mainly of oak and hickory stands.	Native forest	Plantation	Loblolly pine plantation. Intensive management. The study considered biodiversity in early, mid-aged, and mature pine plantations, but the general results did not change.	↘	↘ →	
Cordero-Rivera et al. (2017)	Spain	Native forests dominated by *Alnus glutinosa, Betula alba, Quercus robur, Salix sp., Castanea sativa, Frangula alnus, Corylus avellana* and *Fraxinus excelsior*	Native forest	Plantation	*Eucalyptus globulus*	↘		
Calviño-Cancela et al. (2012)	Spain	Native forests dominated by *Quercus robur*	Native forest	Plantation	*Eucalyptus globulus*	↘		
Goded et al. (2019)	Spain	Native deciduous forest is largely comprised of oak (Quercus robur), chestnut (Castanea sativa) and birch (Betula alba), classified	Native forest	Plantation	*Eucalyptus globulus*	↘	↘	
Hall, 2012	Chile	Temperate rain forest	Natural forest	Pine plantations	Main trend at landscape level: natural forest to plantation	↘		↘
Bremer (2010)	Global		Primary forest	Plantation	Primary forest = old growth (including old European forests > 200 years)	↘		

Chaudhary (2016)	Global		Primary forest	Plantation (timber)	Considers all types of plantation (i.e. mixed - mono; native - exotic; etc.). But the goal is the production of timber, they bring the examples of Teak and Rosewood.	↘
Chaudhary (2016)	Global		Primary forest	Plantation (fuel & pulp)	Considers mainly monoculture plantations of fast-growing crop trees, such as Pinus, Eucalyptus or Acacia. The main goal is production of wood for fuel or pulp for paper.	↘
Chaudhary (2016)	Europe		Primary forest	Plantation (timber)	Considers all types of plantation (i.e. mixed - mono; native - exotic; etc.). But the goal is the production of timber, they bring the examples of Teak and Rosewood.	↘
Chaudhary (2016)	Europe		Primary forest	Plantation (fuel & pulp)	Considers mainly monoculture plantations of fast-growing crop trees, such as Pinus, Eucalyptus or Acacia. The main goal is production of wood for fuel or pulp for paper.	→

5.8.2.5 Synthesis of evidence

Based on the findings from the literature review described above, we defined a few pathways archetypes concerning the impact on biodiversity and ecosystems' condition of interventions related to afforestation and conversion to plantation. Similar considerations as reported in section 5.8.1.4 remain valid.

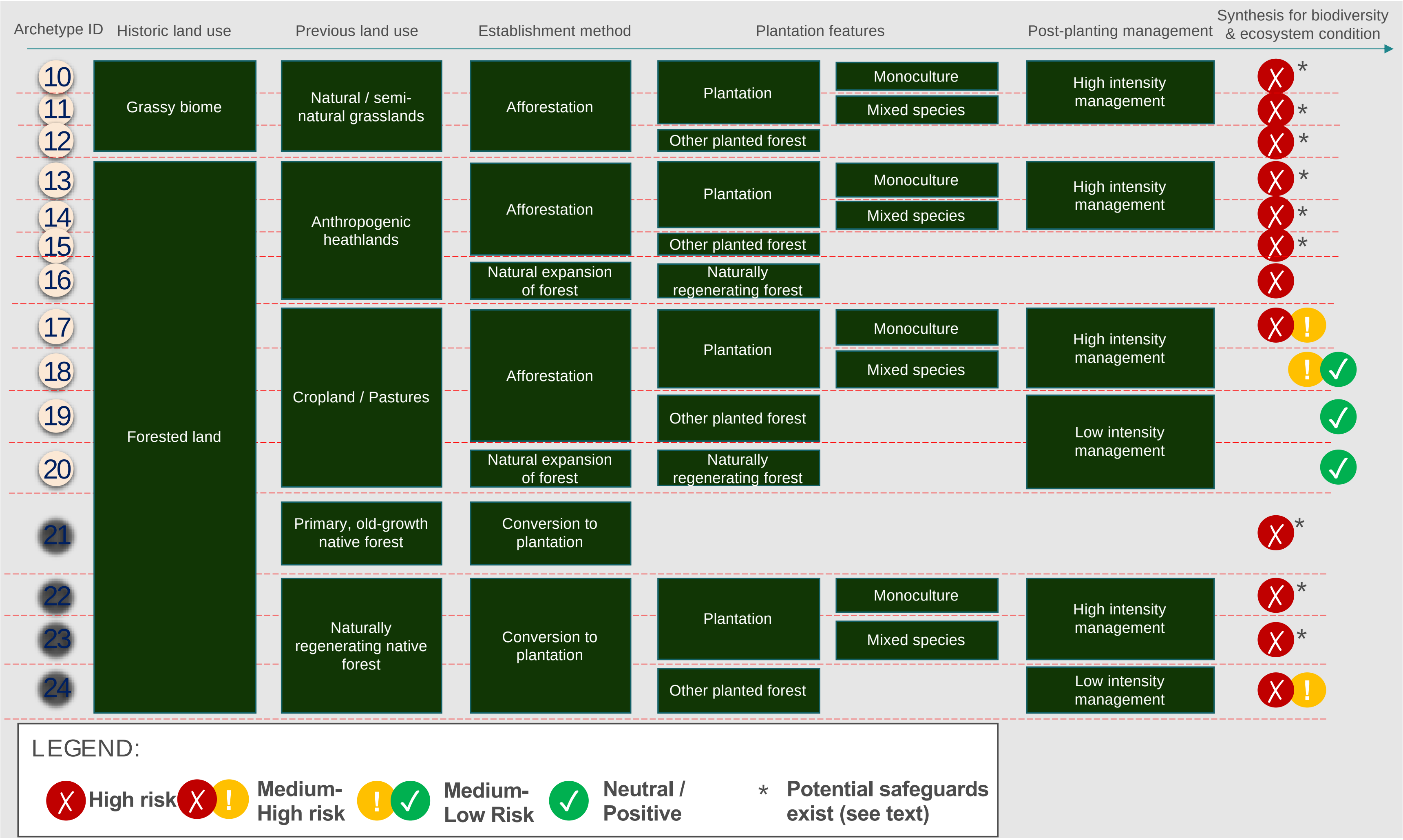


Figure 41. Archetype pathways which represent a synthesis of evidence described in section 5.7.3. The light orange archetype IDs refer to afforestation interventions, while light blue archetype IDs refer to conversion to plantation. The risk qualifiers refer to potential risk, that is, unmitigated by existing legislation, recommendations, or voluntary certification schemes.

The results in Figure 41 can be summarised in the following points:

- The literature review has revealed several pathways which would be detrimental to local biodiversity and ecosystems' condition. Pathways 10-12 reflect the negative impacts of transforming ancient grassy biomes to closed-canopy forests. Pathways 13-16 similarly reflect the risks of tree planting or allowing natural forest regeneration in anthropogenic heathlands, with associated loss of species adapted to open ecosystems. To be noticed that these pathways would be discouraged or altogether forbidden by PEFC standards which state that: 'The standard requires that afforestation of ecologically important non-forest ecosystems shall not occur unless in justified circumstances [...]' (Programme for the Endorsement of Forest Certification, 2018). These interventions would also go against the Pan-European guidelines for reforestation and afforestation (Guideline nr. 18). Nonetheless, the voluntary nature of these guidelines and the potentially limited application of them outside the EU warrant the high-risk qualifier for these pathways.
- Similarly, pathway 21 captures the consensus around the negative impacts of converting primary forests into plantations. This pathway would be also against PEFC and FSC standards which do not accept any forest conversion to plantation, albeit with exceptions. Additionally, old-growth forests in EU account for 4% of the total forest area at best, and most of them are already protected. However, outside of Europe the situation is different and this warrants the high-risk qualifier for this pathway.
- Pathways 17-20 capture the impacts of afforestation of ecosystems deforested in modern times for agricultural purposes. However, they are disaggregated to capture potential different drivers, and thus potential different management objectives. Cunningham et al. (2015) consider four broad categories of environmental benefits that afforestation could provide compared to agricultural land use: carbon sequestration, biodiversity conservation, water yield, and water quality. They openly state that no single type of afforestation strategy will simultaneously maximize all the environmental benefits which is quite clear also from the review presented above. Considering this, pathways 19 and 20 capture situations in which the main goal of afforestation is not only production of wood, but rather a mix of production and biodiversity conservation. Therefore, these forest expansions may take place through active tree planting or by creating the conditions for natural forest succession. The planting strategy and post-planting management have an important role in achieving positive results for biodiversity. Several studies (Calviño-Cancela et al., 2012; Castaño-Villa et al., 2019; MacKay et al., 2014; Paquette and Messier, 2010; Pawson et al., 2013) provide some practical recommendations to enhance biodiversity in planted forests. When the following management strategies are applied (which we term as 'Low intensity management', and is similar to Duncker's definition of 'Close-to-Nature forestry' (Duncker et al., 2012), then the pathways can be considered to have a positive impact on local biodiversity. These pathways are also considered to have improved resilience to natural disturbances and thus lower vulnerability to future climate change (Seidl et al., 2016). To be noticed also that the Pan-European Guidelines on Afforestation and Reforestation also recommend several of these approaches, including: favouring native species (nr. 19), avoiding exotic species with invasive potential (nr. 21), promoting structural and species diversity (nr. 23), promoting landscape connectivity (nr. 24), avoiding chemical substances (nr. 25), and protecting soil and water quality and quantity (nr. 26).
    - At stand level:
        - avoiding clearing natural vegetation prior to planting;
        - planting of native species should be favoured;
        - when planting exotic species, avoid species with potentially invasive characteristics;
        - introduction of structural and species diversity of trees (i.e. polycultures, mixed-species plantings);

    - structural and species diversity is desirable also in the understory, so lower intensity of competition control;
    - long rotation times and maintenance of legacy structures (i.e. mature trees, or dead wood).
  - At landscape level:
    - protection of the remnants of natural and old-growth forest;
    - creation of mosaics of stand ages and tree species, including stands which are left to mature;
    - establishment of corridors linking habitat patches.
- Pathways 17 and 18 reflect conditions in which the plantations are established with the main goal of maximizing productivity of wood, and thus are intensively managed. These pathways would fall in the categories defined by Duncker et al. (2012) as 'Intensive Even-aged forestry' and 'short rotation forestry', including operations such as e.g. short rotations, fertilization, site preparation, removal of dead wood, fast-growing species, etc. These pathways are differentiated based on the planting of a single species or multiple species. Indeed, the literature reviewed has revealed that afforestation by monocultures may have some negative outcomes on local biodiversity and local water cycle. Nonetheless, monoculture plantations can have an important role within the landscape mosaic and even a patchwork of monoculture stands with different single species can create a varied enough structure to maintain or improve local biodiversity compared to degraded former agricultural land (Hua et al., 2016). As a result, pathway 17 is classified with a Medium-high risk level. On the other hand, plantations employing a mixture of tree species might be as, or more, productive than monocultures (Hulvey et al., 2013). This is an ongoing field of investigation, and research is focusing on designing effective species mixtures with high complementarity, so to guarantee high productivity while at the same time increasing resilience and adaptive capacity, as well as improved structural and functional diversity (Forrester, 2014; Liu et al., 2018; Thompson et al., 2014). Additionally, better plantations could be designed to increase resilience to pests and adaptive capacity to climate change (Brockerhoff et al., 2013; Paquette and Messier, 2010; Pawson et al., 2013). Hence, pathway 18 is classified with a Medium-Low risk level, because optimisation of planting design can be achieved.

These pathways might be closely linked to bioenergy demand because, if afforestation efforts are left mainly to economic forces, the push for short-term economic gains might promote the establishment of intensively-managed monocultures based on fast-growing exotic species (Freer-Smith et al., 2019).

- Pathways 22-24 reflect the conclusion by several studies that native naturally regenerated forests should not be converted into plantations. The pathways archetypes reflect only potential direct impacts and exclude indirect factors. This is the reason why pathways 22 and 23 are classified as High-Risk, despite the possibility that plantations establishment might indirectly promote conservation and full protection of natural forests within the landscape (as suggested by Paquette & Messier (2010). If conservation and full protection was made contingent to the conversion, then the overall impact might be different, but it is out of the scope of this synthesis to assess that. Furthermore, the simplified structures of plantations might make them less resilient to natural disturbances and more susceptible to climate change compared to natural forests (Seidl et al., 2016). To be noticed that FSC standard nr. 6.9 explicitly forbid the conversion of natural forests to plantations and standard nr. 6.10 excludes any plantation established in place of natural forests after 1994 from the possibility to be certified, provided certain exceptions.
- Finally, pathway 24 captures situations in which naturally regenerating forest is converted to a planted forest with low management intensity. Castaño-Villa et al. (2019) report this conversion to have a neutral impact on the species richness of birds and even a positive effect on abundance. Nonetheless, it is assigned a Medium-High risk level because many local conditions should be

evaluated to avoid negative impacts. Nonetheless, this pathway may be very relevant because the share of planted forests and plantations is increasing while natural forests are decreasing. Since the demand for timber and especially for bioenergy is increasing, planted forests might carry an increasingly larger role in maintaining suitable habitats for forest biodiversity.

5.9 Synthesis and assessment: climate and ecosystem health

5.9.1 Qualitative assessment

As described in section 5.7, our goal is to try and highlight the potential trade-offs between carbon impact and biodiversity for several bioenergy archetype pathways. While the results of the qualitative assessment for impacts on biodiversity are presented in detail in section 5.8, Table 10 aims to clarify the assessment of carbon impacts.

Table 10. Evaluation of payback times for the pathways archetypes analysed.

Pathway archetype	Expected consequences on carbon accounting of bioenergy
Increased removal of FWD, low stumps, CWD	It depends strongly on the decay rates considered. For instance, (Giuntoli et al., 2015) and (Giuntoli et al., 2016) found that residues with decay rates of 11.5%/year would mitigate climate change compared to natural gas heating and natural gas electricity after about 20 years, but residues with decay rate lower than 2.7%/year would take more than 86 years to payback compared to natural gas heating, or more than a century compared to the current EU power mix. FWD are thus likely to achieve carbon mitigation in a short term. However, decay rates for low stumps have been reported to range between 0.7%/year up to even 11%/year (Persson and Egnell, 2018), depending on climatic conditions and species. Considering a representative decay rate for temperate/boreal forests of between 3 and 6%/year would mean stumps would be unlikely to achieve climate mitigation before 50 years. This is substantiated also by the work of (Laganière et al., 2017). However, we indicate a range of uncertainty across other climate change levels. CWD are very likely to exhibit low decay rates and to have very long payback times.
Conversion of natural forests to fast-growing plantations.	Such a shift leads to a large release of carbon at the time of conversion plus a lower stock of carbon at the maturity of the stand, and potentially lower C-stock in the soil. (Agostini et al., 2014) found that mitigation could indeed be achieved in the medium term, due to the increased rate at which biomass is produced in the plantation. (Sterman et al., 2018a, 2018b) tackled this pathway for US South and found that payback time would be 60-70 years for coal substitution and 120 years for natural gas substitution.
Afforestation	Bioenergy from afforestation activities could achieve carbon mitigation in the short-term, between a few years and a few decades, depending on the vegetation type, amount and status, present in the reforested land as well as the species replanted, their diversity and operations required (Agostini et al., 2014; Gaboury et al., 2009; Lemprière et al., 2013). The resulting carbon balance of afforestation pathways would derive from the net result of two main components: 1) accumulation dynamics of terrestrial C-stock and overall difference at steady state; 2) substitution effects of the bioenergy produced. While the second point would start to have an impact only after the first harvest (i.e. the time of one rotation period, depending on the type of plantation and post-plantation management), the first component might generate c-benefits already in the short term depending on the previous land use and its condition. For instance, the carbon mitigation for natural regenerating forests managed with lower intensity is assumed to be slower compared to plantations due to the lower growth rates. For afforestation of grasslands, even though the review reveals that SOC stocks would be similar if not lower in plantations than in natural grasslands, the additional C-stock sequestered through aboveground biomass growth and the effects of substitution of fossil sources might mitigate climate change within the medium term. To be noticed that indirect effects are excluded from this analysis; large-scale afforestation of former agricultural land might cause indirect land use change which should be evaluated properly.

Additionally, Table 11 summarises the reference / counterfactuals for the biomass or land use for each of the intervention types. These counterfactuals are considered to be the same both when evaluating impacts on ecosystems' condition and on carbon emissions. Due to the qualitative nature of the assessment and the broad-ranging categories chosen, the role of the specific counterfactual chosen might not be a crucial determinant of the final result, nonetheless, the impact assessment presented in Table 12 and Table 13 should always be interpreted as conditional to the counterfactuals considered. To be noticed that all counterfactuals considered reflect a continuation of the 'status quo'.

Table 11. Summary of counterfactuals considered for each intervention type.

Intervention type	Counterfactual for biomass / land	Counterfactual energy source
Logging residues removal	Stem-only harvest. Residues are left on the forest floor to decay at different rates (see Table 10)	Fossil sources
Afforestation	Former land use is maintained	Fossil sources
Conversion to plantation	Management regime of the naturally regenerating forest continues unchanged.	Fossil sources

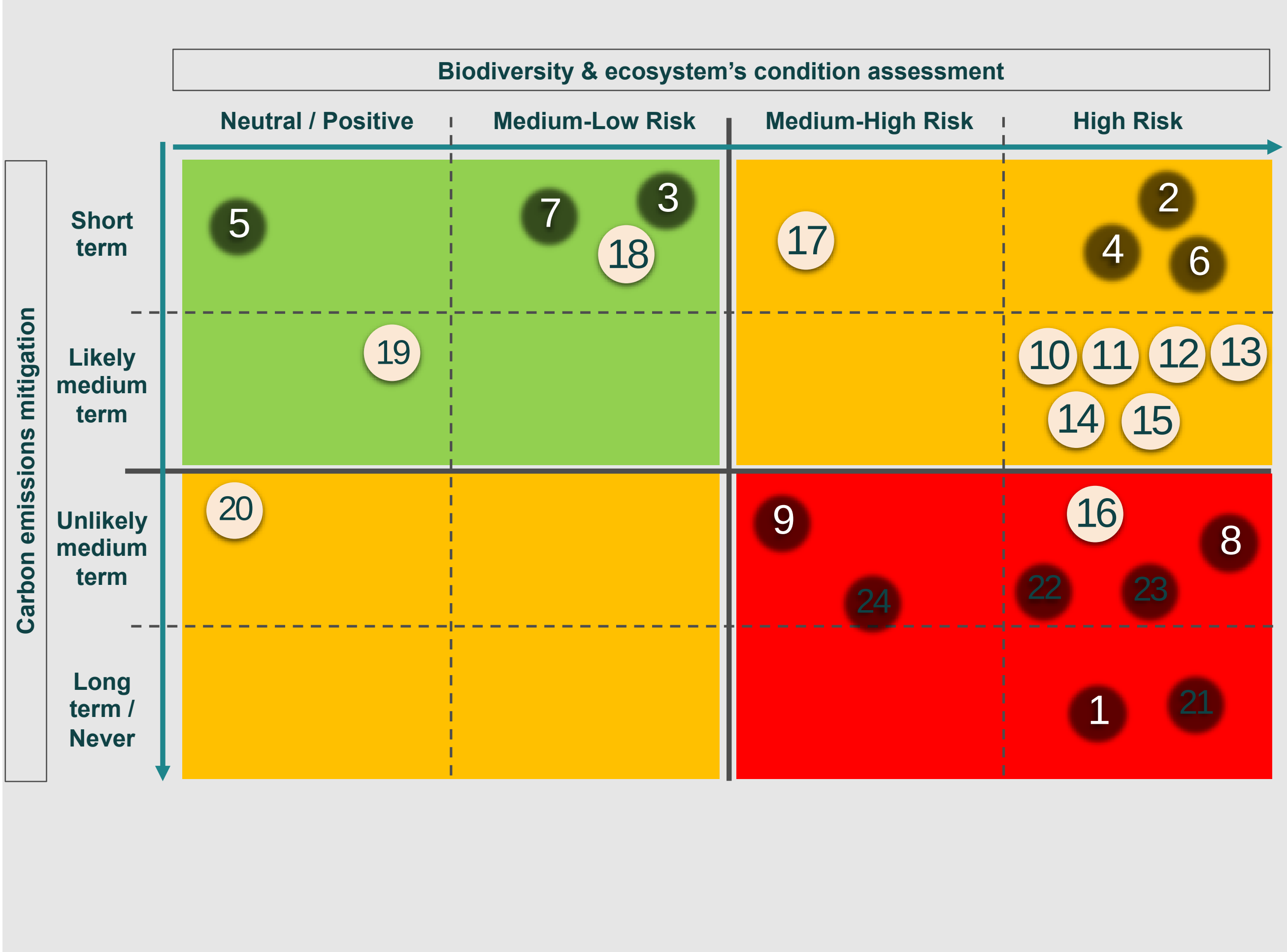
Table 12 and Table 13 summarise all the archetypes and the qualitative assessment for the two impact categories. Figure 42 presents the results graphically to highlight trade-offs. While we think that such a synthetic assessment might provide an initial basis for debate and discussion on the way forward for forest bioenergy, we stress that this assessment is purely qualitative and it inevitably reflects our own judgement; different authors could come to slightly different conclusions reviewing the same exact literature. We thus invite researchers to produce similar assessments, either through qualitative methods similar to ours or employing quantitative tools (where possible and available), to support policymakers in their governance towards bioenergy pathways which mitigate climate change in the short term, while at the same time maintaining or enhancing local forest biodiversity.

Table 12. Summary of biodiversity and carbon accounting assessments per pathway related to removal of logging residues.

Intervention	Archetype ID	Pathway description	Biodiversity impact assessment	Carbon payback time assessment
Logging residues removal	1	Coarse Woody debris	High	Long-term
Logging residues removal	2	Fine woody debris. Slash + foliage/needles	High	Short-term
Logging residues removal	3	Fine woody debris. Slash + foliage/needles	Medium-Low	Short-term
Logging residues removal	4	Fine Woody Debris. Slash	High	Short-term
Logging residues removal	5	Fine Woody Debris. Slash	Neutral	Short-term
Logging residues removal	6	Fine Woody Debris. Slash	High	Short-term
Logging residues removal	7	Fine Woody Debris. Slash	Medium-Low	Short-term
Logging residues removal	8	Low stumps	High	Unlikely medium-term
Logging residues removal	9	Low stumps	Medium-High	Unlikely medium-term

Table 13. Summary of biodiversity and carbon accounting assessments per pathway related to afforestation and plantation.

Intervention	ID	Pathway description	Biodiversity impact assessment	Carbon payback time assessment
Afforestation	10	Natural grassland to monoculture plantation	High	Likely medium-term
Afforestation	11	Natural grassland to polyculture plantation	High	Likely medium-term
Afforestation	12	Natural grassland to other planted forest	High	Likely medium-term
Afforestation	13	Anthropogenic heathland to monoculture plantation	High	Likely medium-term
Afforestation	14	Anthropogenic heathland to polyculture plantation	High	Likely medium-term
Afforestation	15	Anthropogenic heathland to other planted forest	High	Likely medium-term
Afforestation	16	Natural forest expansion on anthropogenic heathland	High	Unlikely medium-term
Afforestation	17	Former agricultural land to monoculture plantation	Medium-High	Short-term
Afforestation	18	Former agricultural land to polyculture plantation	Medium-Low	Short-term
Afforestation	19	Former agricultural land to other planted land managed with low intensity	Neutral-Positive	Short-term / Likely medium-term
Afforestation	20	Natural forest expansion on former agricultural land	Neutral-Positive	Unlikely medium-term
Conversion to plantation	21	Conversion of primary, old-growth forest, to plantation	High	Long-term
Conversion to plantation	22	Conversion of native naturally regenerating forest to monoculture plantation	High	Unlikely medium-term
Conversion to plantation	23	Conversion of native naturally regenerating forest to polyculture plantation	High	Unlikely medium-term
Conversion to plantation	24	Conversion of native naturally regenerating forest to other planted forest managed with low intensity	Medium-High	Long-term



	ID	Pathway description
Logging residues removals	1	Coarse Woody Debris removal
	2	Fine Woody Debris (Slash + foliage/needles) removal above landscape threshold
	3	Fine Woody Debris (Slash + foliage/needles) removal below landscape threshold
	4	Fine Woody Debris (Slash - Coniferous) removal above landscape threshold
	5	Fine Woody Debris (Slash - Coniferous) removal below landscape threshold
	6	Fine Woody Debris (Slash - Deciduous) removal above landscape threshold
	7	Fine Woody Debris (Slash - Deciduous) removal below landscape threshold
	8	Low stumps removal above landscape threshold
	9	Low stumps removal below landscape threshold
Afforestation	10	Natural grassland afforestation with monoculture plantation
	11	Natural grassland afforestation with polyculture plantation
	12	Natural grassland afforestation with other planted forest
	13	Anthropogenic heathland afforestation with monoculture plantation
	14	Anthropogenic heathland afforestation with polyculture plantation
	15	Anthropogenic heathland afforestation with other planted forest
	16	Natural forest expansion on anthropogenic heathland
	17	Former agricultural land afforestation with monoculture plantation
	18	Former agricultural land afforestation with polyculture plantation
	19	Former agricultural land afforestation with other planted land managed with low intensity
	20	Natural forest expansion on former agricultural land
Conversion to plantation	21	Conversion of primary, old-growth forest, to plantation
	22	Conversion of native naturally regenerating forest to monoculture plantation
	23	Conversion of native naturally regenerating forest to polyculture plantation
	24	Conversion of native naturally regenerating forest to other planted forest managed with low intensity

Figure 42. Qualitative assessment of the archetype pathways based on their climate and biodiversity impacts. Black symbols represent pathways referring to 'logging residues removal' intervention, yellow symbols refer to pathways for 'afforestation', and blue symbols refer to 'conversion to plantation' interventions. Uncertainty ranges are placed where payback time for carbon emissions could not be placed within a single one of the already broadly defined levels. The position of the interventions within each sub-section is arbitrary.

The results of the qualitative assessment in Figure 42 show that, on the one hand, it is indeed possible to highlight pathways that can both reduce greenhouse gas emissions in the short term while not damaging, or even improving, the condition of forest ecosystems. Specifically, we find that collecting slash within the limits of locally recommended thresholds could generate energy without damaging forest ecosystems and at the same time likely contributing to reducing GHG emissions. Similarly, afforesting former agricultural land with mixed species plantations or with naturally regenerating forests would enhance the terrestrial sink even before producing biomass for energy and thus would contribute to climate change mitigation, while at the same time improving ecosystems' conditions.

On the other hand, several pathways are categorized in the lose-lose quadrant and should be discouraged. For instance, the removal of CWD and low stumps can be detrimental to forest ecosystems while at the same time likely not contributing to reducing carbon emissions in the short or even medium term compared to fossil sources. However, collection and use of low stumps within locally established thresholds in climate areas with high decay rates could potentially provide carbon emissions mitigation without damaging local biodiversity, but this pathway should be evaluated in each specific case and its benefits should not be taken for granted. Further, as expected, the conversion of natural and old growth forests to plantations aiming to provide wood for bioenergy would be extremely negative for local biodiversity, and at the same time it would provide no carbon mitigation in the short-medium term and should be thus discouraged. Similar considerations are valid also for the conversion of naturally regenerating forests to high-intensity management plantations: the impact on local biodiversity is highly negative while, even though wood production might increase, the benefits in terms of carbon mitigation are only accrued in the medium to long term.

Therefore, the literature review and knowledge synthesis in this chapter show clearly that, depending on the specific ecosystem and intervention concerned in each individual case, evaluating bioenergy interventions only on their potential for carbon emissions reduction risks downplaying the potential negative impacts of such interventions on local ecosystem, with the risk of mitigating the climate crisis while of worsening the biodiversity crisis.

Nonetheless, pathways falling within quadrant 2 and 3 need to be evaluated with care. For instance, as expressed in section 5.7, pathways in quadrant 2 may provide a significant contribution to climate change that would benefit global ecosystems and biodiversity even if local ecosystems are damaged in the process. However, this is a very uncertain trade-off and would be contrary to the precautionary principle, as explained in section 5.7. In this quadrant, for instance, we can find afforestation of former agricultural land with monoculture plantations: this intervention is likely to lead to carbon benefits in the short-term, but the impacts on local ecosystem should be evaluated carefully, for instance in the framework of landscape mosaic management and climate change resilience. Afforestation of natural grasslands or anthropogenic heathlands could also produce carbon benefits in the medium term, but the cost for local biodiversity, especially for species adapted to open spaces, could be devastating. Indeed, these practices are already discouraged within the Pan-European Guidelines for Afforestation and Reforestation, but they are still popular around the world (Veldman et al., 2015b, 2015a). Further in this quadrant, operations which should be already discouraged by sustainable management guidelines are classified: removing slash in very high quantities could be detrimental for local biodiversity.

Pathways in quadrant 3 are probably unlikely to be driven by bioenergy demand, however, they might be definitely valuable for conservation interventions and produce biomass for bioenergy

5.9.2 Future research

We do not claim that our assessment is able to precisely and accurately capture the impacts of each pathway; its utility is rather to act as a basis for further enquiries and research. We thus propose some future research lines which can expand the evidence basis available, within the goal and scope of this chapter. Clearly, further research into bioenergy sustainability will also need to look at integrated assessments accounting for the socioeconomic dimensions which were out of the scope of this work.

Firstly, clearly more empirical research is needed to collect data on the impacts of various forest management practices on ecosystems' conditions and biodiversity attributes, as well as synthesis to bring these findings across disciplinary silos. Efforts in this direction are already on-going, for instance the JRC recently launched the Knowledge Centre for Biodiversity[44] with this exact purpose.

Secondly, concerning the assessment of carbon emissions: the impacts reported here are based on a 'ceteris paribus' perspective, which is apt to capture only small-scale changes and not suitable to capture the overall impact of large-scale deployment of bioenergy, since it excludes market-mediated effects on other sectors. Many holistic assessments of the potential role of bioenergy in climate change mitigation strategies are present in the literature (Giuntoli et al., 2020b). We invite researchers to expand their large-scale systemic assessments to go beyond carbon accounting and include more indicators for biodiversity and ecosystem conditions. While quantitative methods for biodiversity impact assessment are still being developed, the common approach of using forest cover changes as proxies for biodiversity impacts (see e.g. Forsell et al., 2016) is not sufficiently detailed. Changes in management practices can already have significant impacts on ecosystems, which risk being overlooked by using only land-use proxies. We recommend researchers to look at the MAES framework of indicators for a list of relevant attributes and indicators that can be used to quantify impacts on ecosystems' conditions. Aggregation methodologies for several of these indicators could be developed to produce a more synthetic quantitative indicator of impacts on ecosystems.

Thirdly, concerning the assessment of impacts on biodiversity: while we focused on a selected sub-set of interventions and ecosystem attributes, we recommend researchers to expand the investigation to other interventions (e.g. thinning operations, agroforestry establishment, coppice conversion or restoration) and to other attributes (e.g. impacts on physical soil properties).

Finally, the assessment we have done favours synthesis over specific case studies. However, local biotic, abiotic, and climatic conditions play an essential role when it comes to assessing potential impacts on biodiversity, and even when assessing climate change impacts. For instance, the impact of logging residues removals can be largely influenced by locally defined landscape thresholds of removals and climatic conditions influence the decay rate of residues and thus the climate impact of bioenergy produced from them. For this reason, we invite researchers to look at case studies on smaller spatial scales, which could help decision makers in promoting pathways which are win-win at a local scale (see for instance Fingerman and Carman, 2019).

5.10 Conclusions of the chapter and key messages

- The literature review and knowledge synthesis presented in this chapter show that it is possible to highlight win-win forest bioenergy pathways. These can both reduce greenhouse gas emissions in the short term while at the same time not damaging, or even improving, the condition of forest ecosystems

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[44] https://knowledge4policy.ec.europa.eu/biodiversity_en

- Collecting slash within the limits of locally recommended thresholds could be used to generate energy without damaging forest ecosystems while likely contributing to reducing GHG emissions
- Afforesting former agricultural land with mixed species plantations or with naturally regenerating forests would enhance the terrestrial sink even before producing biomass for material and energy uses and thus would contribute to climate change mitigation, while at the same time improving ecosystems' conditions
- Depending on local conditions, determining the decay rates on the forest floor, the removal of Coarse Woody Debris and low stumps can be detrimental to forest ecosystems while at the same time likely not contribute to reducing carbon emissions in the short or even medium term compared to fossil sources. However, collection and use of low stumps within locally established thresholds in climate areas with high decay rates could potentially provide carbon emissions mitigation without damaging local biodiversity; local conditions should be evaluated in these cases
- Conversion of natural and old growth forests to plantations aiming to provide wood for bioenergy would be extremely negative for local biodiversity, and at the same time it would provide no carbon mitigation in the short-medium term and should be thus discouraged. These pathways are likely more relevant for imported biomass than for domestic feedstocks.
- Similar considerations are valid also for the conversion of naturally regenerating forests to high-intensity management plantations: the impact on local biodiversity is highly negative while, even though wood production might increase, the benefits in terms of carbon mitigation are only accrued in the medium to long term
- Existing voluntary standards as well as national guidelines are necessary to mitigate the risks highlighted but could not be sufficient. For instance, we cannot comment whether the local and national interpretation of the certification standards is sufficient to promote healthier ecosystems, and neither we can comment on the enforcement success of such measures. Further, certification standards remain voluntary, and even if certification is widespread in Europe, this is not the case for feedstocks from extra-EU countries.
- More research is needed to collect data on ecosystems' conditions and biodiversity attributes, as well as synthesis to bring these findings across disciplinary silos
- We invite researchers to expand their large-scale systemic assessments to go beyond carbon accounting and include more and more indicators for biodiversity and ecosystem conditions
- The MAES framework of indicators provides a list of relevant attributes and indicators that can be used to assess impacts on ecosystem condition
- This report focusses on a selected sub-set of interventions and ecosystem attributes and we see value in expanding to other interventions (e.g. thinning operations, agroforestry establishment, coppice conversion or restoration) and to other attributes (e.g. impacts on physical soil properties)
- We see the importance of looking at case studies on smaller spatial scales, which could help decision makers in promoting pathways which are win-win at a local scale

On the accounting of the carbon impact of forest bioenergy:

- Through the LULUCF regulation 2018/841, the carbon impact of any change in management or wood use is reflected in the countries' EU climate accounts.

- Managing the risk of unintended outcomes (e.g. excessive use of forest biomass by economic operators, leading to LULUCF accounting debits at country level) requires, first and foremost, a greater awareness by countries of the REDII/ETS-LULUCF links and the associated trade-offs. This awareness should then be reflected in the national relevant plans (National Energy & Climate Plans), through coherent policies and financial incentives at national and local level, combined with a timely and reliable monitoring of the use of wood for energy production.
- As general principle, prioritizing residues and a cascade use of wood remains key for maximizing the positive climate impact of forest bioenergy.
- On imported biomass, criteria should aim to maintain the same environmental standards applied in the EU.

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6 Policy implications and future work

6.1 Policy implications

In this section we summarize the main policy implications of the findings of this report in the framework of existing or planned EU policies. We present these implications divided across the main policy areas that have been addressed in this report for the governance of forest bioenergy at EU level (energy, biodiversity and climate) and make a final transversal remark on data.

6.1.1 Energy legislation

The Directive 2018/2001 on renewable energy (REDII) is a step forward in the governance of environmental sustainability of bioenergy used in the EU, and it provides tools that can be already used to limit or minimize several of the high-risk pathways identified in this report. One of the main goals of the sustainability criteria of REDII (2018/2001) is to ensure that forest biomass used in the EU energy sector is sourced in ways that minimize negative impacts on forest ecosystems and their services. Art.29 paragraphs (6) and (7) are the most relevant with respect to this study. Under this article, bioenergy operators need to provide evidence that the forest biomass is subject to national or sub-national legislation or management systems at the sourcing area level ensuring: (i) legality of harvesting, (ii) forest regeneration, (iii) protection of nature protected areas, (iv) maintenance of soil quality and biodiversity; and (v) maintenance or improvement of the long-term production capacity of the forest. Applied on the consumption side, these criteria affect both to domestic and imported biomass feedstocks.

Crucially, compliance with the REDII criteria for sustainable forest management mentioned above rely, in a first instance, on existing national or sub-national forestry legislation. Therefore, while our focus is on the EU legislative framework, this might be ineffective unless countries themselves, including third countries, check their national sustainable forest management legislation and guidelines against the findings of this report to make sure that lose-lose practices are avoided. At the same time, both EU and national legislations should strive to create the right incentives to promote the win-win pathways and good practices highlighted in this report.

We reckon that many potential impacts associated with the forest management activities reviewed in this study can be effectively minimized through robust implementation of the REDII sustainability criteria for forest biomass, which will be further operationalized in the upcoming EU operational guidance on the evidence for demonstrating compliance with the forest biomass criteria. Our findings demonstrate that the potential negative impacts of removing logging residues could be minimized through criterion (iv) mentioned above. Most voluntary schemes have provisions for CWD retention levels. However, given the incentive created by the REDII to increase the collection and removal of these materials for energy use, it is essential that Member States define appropriate and precautionary landscape retention thresholds across sourcing areas producing bioenergy feedstock for all three categories of residues (slash, low stumps, and CWD), and that they discourage the removal of low-stumps and CWD.

Furthermore, our review highlights the negative impacts of clearing naturally regenerating forests to establish intensively managed plantations, and other planted forests. For instance, plantations established on natural forests (after 1994) are explicitly excluded from FSC certification standards (Forest Stewardship Council, 2015 – Standards 6.9 and 6.10). We recommend that biomass produced from plantations established on recently cleared natural forest cannot be eligible for bioenergy use. This would also remove pressure for future conversions by lowering the demand of wood from these plantations, at least for energy use.

Some of the high-risk pathways identified in this report, though, cannot be effectively discouraged by the existing REDII provision. For this reason we suggest additional possible policy changes within energy and environmental legislative areas. Firstly, the REDII establishes specific no-go areas for agricultural biomass, meaning that biomass for bioenergy cannot be directly produced from land that was, at any time after 2008, classified as: highly biodiverse grasslands, primary forest, highly biodiverse forest, or protected areas. This is not the case for forest biomass. Expanding such a no-go criterion to forest biomass would introduce additional safeguards ensuring that forest biomass for energy is not associated to the afforestation pathways with the most negative impacts, i.e. the ones taking place on natural or also anthropogenic high nature value grasslands or heathlands, and it would also forbid sourcing any wood from plantations established on converted old-growth, primary, forest from being accepted as energy feedstock.

In addition, following the findings in Chapters 2 & 3, an option that could be assessed in terms of its potential to contribute improving reported data quality and completeness, is lowering the threshold of 20 MW for installations producing heating/cooling, electricity and fuels from solid biomass fuels for the purpose of applying sustainability criteria for forest bioenergy (REDII, Art. 29).

6.1.2 Environmental and Climate legislation

Since several of the afforestation pathways assessed in this report are not primarily driven by bioenergy demand, we suppose they should best be tackled through a mix of legislative tools that would then act complementary to the REDII criteria. The EU Biodiversity Strategy for 2030 (COM/2020/380), places an important objective for afforestation in the EU and also calls for a legislative instrument to restore degraded ecosystems, in particular those with the most potential to capture and store carbon and to prevent and reduce the impact of natural disasters.

To minimize the risks of unintended impacts on biodiversity, afforestation interventions should be addressed in foreseen actions of the EU Biodiversity Strategy for 2030 including appropriate safeguards and guidelines to promote ecologically and economically sound interventions. This is particularly relevant for the plans to plant three billion trees, learning from past afforestation initiatives (Lewis et al., 2019). In addition, Europe could act on its global footprint by developing measures to address the potential risks associated to imported biomass (for material or energy use alike) produced from plantations established through harmful afforestation or conversion activities. On this topic, the Commission has committed to delivering, in 2021, a legislative proposal to minimise the risk of deforestation and forest degradation associated with products placed on the EU market.

Moreover, as it has become clear for food crops, any additional demand of wood for bioenergy will simply add up to the overall demand of wood for other uses, meaning that even if wood for energy is subjected to stricter sustainability criteria, wood for other purposes might still be produced through detrimental practices and pathways. As highlighted by the EU Bioeconomy Strategy, a holistic governance is required to move towards a sustainable and circular bioeconomy. Therefore, better defining and expanding sustainable forest management to all forest products consumed in Europe, irrespective of final use and geographical origin, would be a much more effective measure to promote a more sustainable forest-based sector as a whole.

In section 5.3, we clarify the interactions between REDII and LULUCF in accounting the carbon impact of forest bioenergy and identify risks and possible solutions for both domestic and imported biomass.

First, we clarify that the assumption of "carbon neutrality[45]" does not apply when the whole broader EU climate and energy framework post-2020 is considered: REDII and EU Emission

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[45] Agostini et al. (2020) defined this assumption as: "The biogenic carbon neutrality is a very common assumption through which the LCA practitioner avoids accounting for the biogenic carbon cycle by assuming that the

Trading Scheme assume zero-rating of emissions from biomass combustion, because the carbon impact of any change in management or wood use (including related to bioenergy) are reflected in each country's climate accounts, through the LULUCF regulation 2018/841. Despite this, a risk exists of a potential mismatch between policy signals: REDII stimulates bioenergy demand by economic operators (and forest bioenergy policies by counting forest bioenergy towards national renewable energy target), while LULUCF disincentivises countries to harvest beyond certain limits. Managing these risks requires that national policies (National Energy & Climate Plans) are guided by a full awareness of the bioenergy-LULUCF links, avoiding that financial incentives to the use of forest bioenergy shift the balance towards undesirable outcomes (e.g. excessive use of forest biomass by economic operators, leading to LULUCF accounting debits at country level). This, in turn, necessarily requires a timely and accurate monitoring: without reliably knowing how much and what type of bioenergy is used, no effective policy can be planned or implemented. The ongoing revision of RED II and LULUCF could also make their linkages more evident, in order to facilitate understanding and awareness amongst Member States, academia, stakeholders and citizens.

As general principle, prioritizing residues without any other use of higher added-value, as well as a circular use of wood remains key for maximizing the positive climate impact of forest bioenergy. Although it was often not possible to translate this principle into EU norms, qualitative criteria have been proposed in the literature to identify bioenergy pathways with low risks of increased GHG emissions compared to fossil fuels. These criteria may help the implementation of energy and climate legislation by countries and bioenergy operators.

Second, since the REDII Art. 29(7) criteria for the carbon accounting of imported forest biomass primarily relies on the fulfilment of the economy-wide National Determined Contributions (NDCs) under the Paris Agreement, the robustness the associated carbon accounting depends also on the LULUCF ambition and monitoring capacity of countries exporting wood for energy to the EU. To this regard, the efforts to increase the ambition and transparency of NDCs (including the need of progression over previously submitted NDCs) are being done under Paris Agreement. For countries not having an NDC or not having LULUCF within their NDCs, it is crucial that evidence is provided that carbon stocks and sinks are maintained or enhanced for any imported biomass, at both the national or the relevant subnational level.

In addition, although the LULUCF regulation 2018/841 is a step forward towards a complete forest GHG accounting in the EU – including the setting of the Member States' Forest Reference Levels for the period 2021-2025 -, we note that accounting rules under LULUCF complicates the communication and the perception of the bioenergy accounting. This is because these accounting rules filter the GHG fluxes as compared to what is "seen" by the atmosphere and reported in GHG inventories. These rules were originally designed mainly to address concerns such as lack of confidence in LULUCF estimates, additionality, permanence, risk to dilute (the already non-ambitious) efforts in other sectors. Importantly, these rules have been always applied when LULUCF was not included in the base year upon which the percentage of reduction was calculated (i.e. under the Kyoto Protocol and for the –40% EU target in 2030). The "credits" or "debits" resulting from the application of the accounting rules were then added on top of the other sectors to assess compliance towards the emissions reduction target.

The recent Commission Communication 2020/562 on "Stepping up Europe's 2030 climate ambition" introduces some novelty that may change the current landscape on LULUCF (and therefore also on bioenergy) accounting. Specifically, in line with the economy-wide target recommended by the Paris Agreement, 2020/562 proposes to include the full LULUCF sink in the 1990 base year used to compute the -55% emission reduction in 2030. We note that a relevant

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carbon emitted from biomass combustion or decomposition will be reabsorbed by the growing plants on a time scale significantly shorter than the relevant scale of the analysis".

consequence is that, for methodological consistency (to allow a like-with-like comparison), the full LULUCF sink reported in GHG inventories will need to be added also when checking the compliance towards the 2030 target. This would potentially mean treating LULUCF like any other sector, i.e. with no or limited filtering of the GHG fluxes reported in the GHG inventories through a complex set of accounting rules. While this change may raise some potential concern (e.g. on the additionality and permanence of these GHG fluxes), we also see opportunities of additional improvements relative to the current situation. First, this would represent a step towards the EU 2050 climate neutrality target, where the full size of LULUCF emissions and removals will be counted, because this is what ultimately matters for the atmosphere. Second, treating the LULUCF sector like any other sector from 2030 would introduce an important simplification of the LULUCF jargon, facilitate communication (i.e. it would be more evident that all the carbon impact of bioenergy is accounted for) and thus bring more transparency also in the accounting of forest bioenergy emissions.

6.1.3 Data

Forests provide a wide range of ecosystem services, such as carbon storage and sequestration, habitat provision, water regulation (quality, quantity, flow), regulation of air quality, soil erosion control, recreation, wood and non-wood products. They have furthermore been identified as part of the solution to many global challenges. However, for such an important contributor to EU policies, data availability regarding the entire forest-based sector is surprisingly scarce, patchy and outdated. It is clear that the use of woody biomass for energy takes place in a complex framework. Thus, to analyse these different aspects, various datasets must be used: questionnaires, official statistics and statistics collected ad hoc for the purposes of the study at hand. The interlinkages between the forest-based industries and wood-based energy production are such that data on all fronts are required to fully understand the situation in the EU regarding forest bioenergy.

The current significant gap in data represents a major obstacle to the effective governance of wood-based bioenergy policies at national scale. Efforts to review reporting procedures should be encouraged, aiming at better correspondence between data sources and reducing the notable inconsistencies in the data. Without reliably knowing how much and what type of forest biomass is used for bioenergy, no effective policy can be implemented, and disagreements about its impacts will persist. With the entry into force of the Governance of the Energy Union Regulation, many of the data will be regularly reported by the Member States, although important ones will still be on a voluntary basis. This might be an important step towards the needed clarity, nevertheless a quality checked, harmonised, timely and comprehensive data collection regarding the EU forest-based sector is critical to effectively monitor the use of woody biomass for energy as well as for future research.

6.2 Future research work, improving data and knowledge

The overview of the existing forest biomass data in Europe (Chapter 4) showed that the NFIs provide valuable reference statistics but they refer to different definitions, periods and spatial scales, with large variability especially in their temporal frequency. For these reasons, their use for a pan-European assessment requires a substantial harmonisation effort, which highlights the importance of the wide collaboration with national forestry experts.

Efforts in Europe such as the Forest Information System for Europe and the EU Observatory are contributing concretely to improving this situation. ENFIN (European network of NFIs) is valuable because it brings together NFIs from different countries to work out common definitions and approaches, however more effort is needed to encourage sharing of knowledge and information about this resource that has a common benefit to us all.

The Bioeconomy Monitoring system under development is a unique opportunity to put together the different statistics on biomass production, supply, use and the related impacts along the sustainability dimensions. Pursuing this effort will provide better information on the interrelations between the use of woody biomass for energy and other uses of biomass. Also, confronting the various sources will be key to crosscheck, harmonise the data and fill the gaps. Moreover, timeseries for the different indicators should be built to make it possible to evaluate the progresses made and the issues raised by the development of biomass use.

Earth Observation can integrate and support ground-based data with wall-to-wall forest monitoring over large areas with high spatial resolution in a timely, consistent and independent way and are being increasingly introduced in the European NFI systems. New technologies are expected to substantially improve the knowledge of the spatial distribution and dynamics of forest biomass, and thus better assess the forest resources currently available and their potential role in the bioeconomy.

To explore the possible impact of a further development of the use of woody biomass for energy from an ecological, environmental, social and economic perspective, there is a need for complementary information, also spatially explicit, on the characteristics of forest management in Europe and its local implications.

Our assessment of the potential impacts of forest management practices on biodiversity could be developed further. We proposed three main research lines: 1. Expand the empirical research and knowledge synthesis basis to collect data on the impacts of forest management interventions on local biodiversity; 2. Expand the investigation of potential impacts of additional interventions to the ones assessed in this report (e.g. forest restoration, thinning, coppice restoration etc…), also focusing on specific case studies. 3. Develop integrated assessment exercises to evaluate simultaneously potential impacts of large-scale bioenergy deployment on climate change and on forest ecosystems. These exercises require the development of multidisciplinary modelling systems, combining land use, ecosystem management, economic and social components.

This report, as well as the future research lines proposed, focus on expanding the evidence basis at the disposal of decision makers. Differences in ethical values on the interaction between humans and nature clearly play a role in defining what ‘sustainable management’ means. We think that if we want to de-toxify the debate surrounding the sustainability of forest bioenergy, these divergences in values should be acknowledged and discussed explicitly also within the scientific community. The JRC, as organization at the interface between science and policy, is in a perfect position to lead this effort.

List of definitions

These definitions are part of the Bioeconomy glossary stored by the Knowledge Centre for Bioeconomy[46] and developed in the context of the JRC Biomass study.

Above ground biomass	All biomass of living vegetation, both woody and herbaceous, above the soil including stems, stumps, branches, bark, seeds, and foliage. (source: FAO 2018)
Afforestation	Establishment of forest through planting and/or deliberate seeding on land that, until then, was under a different land use, implies a transformation of land use form non-forest to forest. (source: FAO 2018)
Below ground biomass	All biomass of live roots. Fine roots of less than 2 mm diameter are excluded because these often cannot be distinguished empirically from soil organic matter or litter. (source: FAO 2018)
Biodiversity	Biological diversity (or biodiversity) is defined in the UN Convention on Biological Diversity as: "the variability among living organisms from all sources, including, 'inter alia', terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems. (source: UNEP 1992)
Bioenergy	Energy made available by the combustion of materials derived from biological sources. (source: EEA glossary, https://www.eea.europa.eu/help/glossary/chm-biodiversity/bioenergy)
Biomass	The biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin. (source: EU 2009)
Black liquor	By-product from chemical and semichemical wood pulp industry. (own elaboration)
By-products	A secondary product which is made incidentally during the production of something else. Example: Sawdust when sawing timber. (source: ISO 16559:2014(en) Solid biofuels — Terminology, definitions and descriptions)
Cascade use	The efficient utilisation of resources by using by-products and recycled materials for material use to extend total biomass availability within a given system (adapted from Vis el al. 2016)
CO_2 equivalent	A metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. (source: EEA glossary, based on IPCC Third Assessment Report, 2001)
Deadwood / dead wood	All non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps. (source: FAO 2018)
Disturbance (natural)	Damage caused by any factor (biotic or abiotic) that adversely affects the vigor and productivity of the forest and which is not a direct result of human activities. (source: FAO 2018)
Fellings	Average standing volume of all trees, living or dead, measured overbark to minimum diameters as defined for “Growing stock” that are felled during the given reference period, including the volume of trees or parts of trees that are not removed from the forest, other wooded land or other felling site. Includes: silvicultural and pre-commercial thinnings and cleanings left in the forest; and natural losses that are recovered (harvested). (source: Forest Europe 2015)
Forest	Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban use. (source: FAO 2018)
Forest available for wood supply	F Forests where any environmental, social or economic restrictions do not have a significant impact on the current or potential supply of wood. These restrictions can be established by legal rules, managerial/owner’s decisions or because of other reasons. (source: Forest Europe 2015)
Forest management	Any activity resulting from a system applicable to a forest that influences the ecological, economic or social functions of the forest (source: EU 2013)
Forest-based sector	Term covering forest resources and the production, trade and consumption of forest products and services (source EC 2013a).
Forestry	The science and craft of creating, managing, using, conserving, and repairing forests, woodlands, and associated resources for human and environmental benefits.
Fuelwood	Roundwood that will be used as fuel for purposes such as cooking, heating or power production. It includes wood harvested from main stems, branches and other parts of trees (where these are harvested for fuel) and wood that will be used for charcoal, wood pellets and other agglomerates. (source: Eurostat et al. 2016)
Gross annual increment	Annual volume of increment of all trees. Includes the increment of trees which have been felled or have died during the reference period. (source: adapted from Forest Europe 2015)
Growing stock	Volume over bark of all living trees with a minimum diameter of 10 cm at breast height (or above buttress if these are higher). Includes the stem from ground level up to a top diameter of 0 cm, excluding branches. (source: FAO 2020)
Habitat	The place or type of site where an organism or population naturally occurs. (source: UNEP 1992)
Industrial roundwood	It includes all roundwood except fuelwood. (source: Eurostat et al. 2016)

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[46] https://knowledge4policy.ec.europa.eu/bioeconomy/glossary_en

Life cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. (source: EC 2013b)
Life cycle approach	Takes into consideration the spectrum of resource flows and environmental interventions associated with a product from a supply-chain perspective, including all stages from raw material acquisition through processing, distribution, use, and end-of-life processes, and all relevant related environmental impacts (instead of focusing on a single issue). (source: EC 2013b)
Logging residues	The wood left in the forest after forestry logging operations. These residues generally include woody debris from final felling (e.g. branches, leaves, stumps, roots, tops, bark), small trees from thinning and clearing operations and generally un-merchantable stem wood. (source: Camia et al. 2018)
Native forest	Naturally regenerated forests of native tree species
Native tree species	A tree species occurring within its natural range (past or present) and dispersal potential (i.e. within the range it occupies naturally or could occupy without direct or indirect introduction or care by humans). (FAO 2018)
Net annual increment	Annual volume of gross increment less that of natural losses on all trees. (source: adapted from Forest Europe 2015)
Net trade	Import minus export.
Other agglomerates	Agglomerates other than wood pellets, for example briquettes or logs. (source: Eurostat et al. 2016)
Other wood components	It refers to branches, stumps and tops. (source: Camia et al. 2018)
Other wooded land	Land not classified as "Forest", spanning more than 0.5 hectares; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds in situ; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use. (Source: FAO 2018)
Post-consumer wood	Recovered used wood from transport (pallets), private households, as well as used wood arising from construction or demolition of buildings or from civil engineering works, suitable for use as a fuel or for production of wood pellets and particle board. (source: UNECE/FAO Forestry and Timber Section 2018)
Primary forest	Naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed (source: FAO 2018)
Primary woody biomass	All roundwood felled or otherwise harvested and removed. It comprises all wood obtained from removals, i.e., the quantities removed from forests and from trees outside the forest, including wood recovered due to natural mortality and from felling and logging. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form, e.g., branches, roots, stumps and burls (where these are harvested) and wood that is roughly shaped or pointed. (source: Eurostat et al. 2016)
Pulpwood	Roundwood that is primarily intended for the production of pulp, particleboard or fibreboard. It includes: roundwood (with or without bark) in its round form or as splitwood or wood chips made directly (i.e. in the forest) from roundwood. (source: Eurostat et al. 2016)
Removals	The volume of all trees, living or dead, that are felled and removed from the forest, other wooded land or other felling sites. (source: Eurostat et al. 2016)
Roundwood	All roundwood felled or otherwise harvested and removed. It comprises all wood obtained from removals, i.e. the quantities removed from forests and from trees outside the forest, including wood recovered from natural, felling and logging losses during the period, calendar year or forest year. It includes all wood removed with or without bark, including wood removed in its round form, or split, roughly squared or in other form (e.g. branches, roots, stumps and burls - where these are harvested - and wood that is roughly shaped or pointed). It is an aggregate comprising fuelwood, including wood for charcoal, and industrial roundwood (wood in the rough). (source: Eurostat et al. 2016)
Salvage logging	Any harvesting activity consisting of recovering timber that can still be used, at least in part, from lands affected by natural disturbances. (source: EU 2013.)
Sawdust	Fine particles created when sawing wood. - Note: Most of the material has a typical particle length of 1 to 5 mm. (source: FAO 2004)
Sawnwood	Wood that has been produced from roundwood, either by sawing lengthways or by a profile-chipping process and that exceeds 6 mm in thickness. It includes planks, beams, joists, boards, rafters, scantlings, laths, boxboards and "lumber", etc., in the following forms: un-planed, planed, end-jointed, etc. (source: Eurostat et al. 2016)
Secondary woody biomass	It includes forest industry by-products, bark, and recovered post-consumer wood.
Short rotation coppice	Woodland which has been regenerated from shoots formed at the stumps of the previous crop trees, root suckers, or both, i.e., by vegetative means. Normally grown on a short rotation for small material, but sometimes, e.g. some eucalypt species, to a substantial size. (Source: UNECE/FAO Forestry and Timber Section 2018)
Solid wood equivalent (SWE)	Amount of solid wood fibre contained in the product. It is the roundwood equivalent volume (green volume prior to any shrinkage) needed to produce the product when there are no losses or wood residues. (source: UNECE/FAO, 2010.)
Stemwood	The wood of the stem(s) of a tree, i.e. the above ground main growing shoot(s). Stemwood includes wood in main axes and in major branches where there is at least X m of 'straight' length to Y cm top diameter. (Source: Camia et al. 2018). Stemwood, within the context of this study, is the over bark biomass of the stem from 15 cm height (thus excluding the stump) up to a minimum top diameter of 9 cm.
Sustainable forest management	Stewardship and use of forest lands in a way and at a rate that maintains their productivity, biodiversity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions at local, national and global levels and that does not cause damage to other ecosystems. (source: Forest Europe 2011)

	A dynamic and evolving concept intended to maintain and enhance the economic, social and environmental value of all types of forests, for the benefit of present and future generations. (UNFPS 2017)
Thinnings	A cultural treatment made to reduce stand density of trees primarily to improve growth, enhance forest health, or recover potential mortality. (source: Deal, 2015)
Tree	A woody perennial with a single main stem, or in the case of coppice with several stems, having a more or less definite crown. (source: FAO 2020)
Wood-based panels	Aggregate product category comprising veneer sheets, plywood, particle board, and fibreboard. (source: Eurostat et al. 2016)
Wood chips and particles	Wood that has been reduced to small pieces and is suitable for pulping, for particle board and/or fibreboard production, for use as a fuel, or for other purposes. It excludes wood chips made directly in the forest from roundwood (i.e. already counted as pulpwood or fuelwood). (source: Eurostat et al. 2016)
Wood pellets	Agglomerates produced either directly by compression or by the addition of a binder in a proportion not exceeding 3% by weight. Such pellets are cylindrical, with a diameter not exceeding 25 mm and a length not exceeding 100 mm. (source: Eurostat et al. 2016)
Wood pulp	Fibrous material prepared from pulpwood, wood chips, particles or residues by mechanical and/or chemical process for further manufacture into paper, paperboard, fibreboard or other cellulose products. It represents the sum of mechanical and semi-chemical wood pulp, chemical wood pulp and dissolving wood pulp. (source: Eurostat et al. 2016)

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List of acronyms and abbreviations

Acronym	Definition
AGB	Above Ground Biomass
CBM	Carbon Budget Model
CCI	Climate Change Initiative
CFRQ	Collaborative Forest Resources Questionnaire
CWD	Coarse Woody Debris
EEA	European Environmental Agency
ENFIN	European National Forest Inventory Network
ETS	Emissions Trading System
ESA	European Space Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAWS	Forest Available for Wood Supply
FISE	Forest Information System for Europe
FRA	Forest Resource Assessment
FRL	Forest Reference Level
FSC	Forest Stewardship Council
FW	Fuel wood
FWD	Fine Woody Debris
GAI	Gross Annual Increment
GDP	Gross Domestic Product
GHG	Greenhouse Gases
ha	Hectare
H&P	Heat and power
HWP	Harvested Wood Products
IAM	Integrated Assessment Model
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRW	Industrial roundwood
JFSQ	Joint Forest Sector Questionnaire
JRC	Joint Research Centre
JWEE	Joint Wood Energy Enquiry
LCA	Life Cycle Assessment
LULUCF	Land Use, Land-Use Change and Forestry
MAES	Mapping and Assessment of Ecosystems and their Services
MCPFE	Ministerial Conference on the Protection of Forests in Europe
Mg	Mega grams
m^3	Cubic meter
Mm^3	Million cubic meters
MJ	Mega Joules
MS	(EU) Member State

Acronym	Definition
Mt	Million tonnes
NAI	Net Annual Increment
NASA	National Aeronautics and Space Administration
NCS	Natural Climate Solutions
NDC	Nationally Determined Contributions
NECP	National Energy and Climate Plans
NFI	National Forest Inventory
NREAP	National Renewable Energy Action Plan
NUTS	Nomenclature of Territorial Units for Statistics
o.b.	Over bark
OWC	Other Wood Components
PCW	Post-consumer wood
PECF	Programme for the Endorsement of Forest Certification
RED	Renewable Energy Directive
SC	Specific Contract
SCI	Species of Conservation Interest
SFM	Sustainable Forest Management
SOC	Soil Organic Carbon
SoEF	State of Europe's Forests
SWE	Solid Wood Equivalent
tdm	Tonnes of dry matter
TJ	Terajoule
toe	Ton of oil equivalent
u.b.	Under bark
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
WRB	Wood Resource Balance

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Authors & their contributions

Andrea Camia obtained his PhD in Forest Sciences in 1995. From 1996 to 2003 he was adjunct professor at the University of Torino and the University of Palermo (Italy). Andrea has been at the Joint Research Centre since 2004, he is senior researcher and has overseen the research presented in this report in his role as leader of the Bioeconomy Project at the JRC Directorate for Sustainable Resources, encompassing the coordination of the JRC Biomass Study and the Bioeconomy Knowledge Centre. As of June 2020, his research focus has shifted to Earth Observation and Copernicus products and services.

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Nicolas Robert holds a degree in engineering and a master's degree in agriculture from the National Institute of Agronomy Paris-Grignon as well as a PhD in environmental economics from AgroParisTech (France). Nicolas joined the bioeconomy unit of JRC in 2016. His research focuses on the socioeconomic implications of developing the forest-based bioeconomy in the European Union. The main aspects concern forest-based and forest-related employment as well as forest accounts. He also contributes to the review of the cross-sectorial estimates of the biomass available in Europe. He worked previously on forest inventory, including the harmonisation of forest inventories in Europe, forest growth modelling, carbon flows in the forest-based sector as well as the supply and valuation of forest ecosystem services in Europe and the Mediterranean basin. Nicolas is the main author of Chapter 2.

Ragnar Jonsson has an M.Sc. in Forestry at Swedish University of Agricultural Sciences (SLU), M.Sc. in social sciences at Lund University, and D. Tech. at Växjö University. Ragnar's work centres on the analysis of forest resources and forest products needs at European level, including wood and non-wood products. His work experience includes producing and analysing projections of wood products demand on European level, research in integrated management of European forest landscapes, and research on the current state of forest management and prospects for increasing the supply of woody biomass within northern Europe. Ragnar conducted econometric analysis of wood-product markets and producing projections of wood products supply and demand at global level for the FAO. Ragnar is the main author of Chapter 3.

Valerio Avitabile is a forester with expertise on forest monitoring and assessment from local to global scale. He works at the JRC since 2016 on the analysis and integration of spatial data on forest resources in Europe. His research activities focus on the assessment of forest biomass and the integration of field and remote sensing data streams. Valerio holds a doctoral degree in Geography from the Friedrich-Schiller University (Jena, Germany) and spent 5 years as researcher in the Laboratory of Geoinformation and Remote Sensing at Wageningen University (The Netherlands), where he collaborated with the main institutes involved with forest monitoring from space, as the FAO, the ESA and the Wood Hole Research Centre. His skills include image processing, analysis of forest data and spatial modelling. Valerio is the main author of Chapter 4.

Jacopo Giuntoli obtained his PhD from Delft University of Technology in 2006 and an MSc. in Energy Engineering from Politecnico di Milano in 2005. Jacopo's work focuses on evaluating the environmental sustainability of biofuels and bioenergy through Life Cycle Assessment. Jacopo supported the EU Commission policies on sustainable bioenergy and where he was responsible for the calculations for default GHG emissions of solid and gaseous bioenergy in the EU Renewable Energy Directive. In 2018 Jacopo worked for the International Council on Clean Transportation studying how forest management choices influence the climate change mitigation potential of forest bioenergy. Jacopo is the main author of Chapter 5.

Giacomo Grassi has been a senior scientific officer at the Joint Research Centre (JRC) of the European Commission (EC), since 2005. He has a PhD in Forest Ecology. He leads the group on "Land Use, Land Use Change and Forestry" (LULUCF), dealing with the estimation of CO2 fluxes from managed terrestrial ecosystems (mainly forests), and their reporting to the UN Framework Convention on Climate Change (UNFCCC). He provides scientific support in the design of policies at EU level (e.g. the forest reference levels under the post-2020 LULUCF Regulation) and under the Paris Agreement. Giacomo is an expert reviewer of LULUCF GHG inventories for the UNFCCC and lead author of several IPCC reports ("2013 Supplementary Guidance under the Kyoto Protocol", "Methodological Refinement of the 2006 Guidelines for GHG inventories" and "Special Report on Climate Change and Land", "6th Assessment Report – WGIII"). Giacomo has contributed to Chapter 5.

Noemi E. Cazzaniga holds a Ph.D. in Geodesy and Geomatics and a Degree in Environmental and Land Planning Engineering. She worked for ten years at Politecnico di Milano (Technical University) before joining the JRC in 2016. Noemi is the database manager and has contributed to the analysis in Chapter 3.

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José I. Barredo is a senior researcher at the Joint Research Centre of the European Commission. He is a geographer (PhD) specialised in forest ecosystem services, biodiversity, climate change and geoinformatics. José has contributed to Chapter 5.

Annex

Logging residues

Scopus TITLE-ABS-KEY ("logging residues" OR "deadwood" OR "dead-wood" OR "dead wood" OR "slash" OR "stump" OR "stumps" OR "whole tree harvest") AND TITLE-ABS-KEY ("*diversity" OR "ecosystem health" OR "ecosystem condition" OR "soil" OR "species" OR "ecosystem function" OR "ecosystem structure" OR "population" OR "abundance" OR "richness" OR "genetic") AND TITLE-ABS-KEY ("review" OR "meta-analy*") AND SUBJAREA ("AGRI" OR "ENVI" OR "EART" OR "ENER" OR "ECON") AND NOT TITLE-ABS-KEY ("slash-and-burn" OR "slash and burn")

Afforestation

Scopus TITLE-ABS-KEY ("afforestation" OR "reforestation") AND TITLE-ABS-KEY ("*diversity" OR "ecosystem health" OR "ecosystem condition" OR "soil" OR "species" OR "ecosystem function" OR "ecosystem structure" OR "population" OR "abundance" OR "richness" OR "genetic") AND TITLE-ABS-KEY ("review" OR "meta-analy*") AND SUBJAREA ("AGRI" OR "ENVI" OR "EART" OR "ENER" OR "ECON"

KJ-NA-30548-EN-N

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of the European Union

doi:10.2760/831621

ISBN 978-92-76-27867-2